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STUDY OF HORIZONTAL-SPRAY FLUX FORCE/CONDENSATION SCRUBBER

by

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FOREWORD

This report, "Study of Horizontal Spray Flux Force/Condensation Scrubber," is the final report submitted to the Industrial Environmental Research Laboratory for E.P.A. Contract No. 68-02-1328, Task No. 10.

The principal objective of this program was to experimentally evaluate fine particle collection in a laboratory pilot scale flux force/condensation (FF/C) scrubber and to determine the feasibility of application of FF/C scrubbing to industrial sources. The main activities under the scope or work were:

Based on the results of the previous theoretical and experimental study of FF/C scrubbing;

1. Design and fabricate the pilot scale horizontal spray scrubbers large enough for the exploration of scale-up problems.
2. Conduct a laboratory pilot experimental program to:
   A. Determine feasibility for fine particle collection.
   B. Develop design equations and scale-up criteria.
   C. Determine optimum operating conditions for FF/C scrubbing.
   D. Investigate potential operational and maintenance problems.
   E. Determine effects of particle size distribution on the performance of FF/C scrubbers.
3. Prepare revised engineering and cost analysis to incorporate results of the experimental study.
4. Recommend a detailed industrial pilot test program.

Dr. Leslie E. Sparks of the Industrial Environmental Research Laboratory, U.S. Environmental Protection Agency was the Project Officer for this program.

Dr. Seymour Calvert of Air Pollution Technology, Inc. was the Project Director.

ABSTRACT

This report presents the results of a laboratory pilot scale evaluation of a Flux Force/Condensation (FF/C) scrubber for the collection of fine particles. FF/C scrubbing includes the effects of diffusiophoresis, thermoporesis, Stefan flow and particle growth due to the condensation of water vapor. Fine particles are those smaller than 2 microns in diameter.

The FF/C scrubber tested was of horizontal spray configurations. Effects of the scrubber configurations, liquid and gas flowrates, particle number concentration and the amount of vapor condensation were studied experimentally. Fractional particle penetrations were measured with cascade impactors and are presented in terms of particle penetration as a function of particle size. The experimental results are compared with predictions from mathematical models.

Optimum operational regions and the technical and economic feasibility of FF/C scrubbing are determined and demonstrated for a fine particle pollution source. It was confirmed that FF/C scrubbing is an attractive control method for fine particles when high efficiency is required or when the gas is hot enough to evaporate the necessary water vapor for condensation in the scrubber. A program to demonstrate FF/C scrubbing at pilot scale for the control of fine particulate emissions from industrial sources is described.

This report was submitted by Air Pollution Technology, Inc. in fulfillment of Contract No. 68-02-1328, Task No. 10, under the sponsorship of the Environmental Protection Agency. Work was completed on December 14, 1974.

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NOMENCLATURE

A = constant
B = constant
c_p = particle mass concentration, g/DNm^3 gas
C' = Cunningham correction factor, dimensionless
d = diameter, cm, μm or μmA≡ μm $(g/cm^3)^{1/2}$
d_{pg} = mass mean diameter, μm or μmA
E = efficiency, fraction or %
G = gas rate, Kg/hr-m^2 column area
L = liquid rate, Kg/hr-m^2 column area
n = particle number concentration, no./cm^3
Pt = penetration, fraction or %
Pt_d = penetration for particle diameter "d_p", fraction or %
$\overline{Pt}$ = overall penetration, fraction or %
ΔP = pressure drop, cm W.C. or atm
q = vapor condensed per particle, g
q_m = vapor condensed per unit mass of inlet particles, mass fraction
q' = condensation ratio, g vapor condensed/g dry gas
R_n = particle concentration ratio defined in eq. (4-7), dimensionless
u = velocity, cm/sec
r = radius, cm, μm, or μmA
v = cumulative volume concentration, cm^3/cm^3
V_s = gas volume swept per volume of spray, m^3/l
σ_g = geometric standard deviation, dimensionless
ρ = density, Kg/m^3 or g/cm^3

Subscripts

a = aerodynamic
d = drop
i = inlet
o = outlet
p = particle
t = total

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CHAPTER 1

INTRODUCTION

A major drawback of present day scrubbers is the large energy expenditure required to achieve high removal efficiencies for fine particles in the size range of 0.1 to 2 microns in diameter. This is due to the decreased effectiveness of the inertial and diffusional collection mechanisms for particles in this size range. Flux force and water vapor condensation effects have the potential to improve fine particle collection in low energy scrubbers.

In this report, flux forces are defined as those caused by thermophoresis and diffusiophoresis (which includes the diffusiophoretic and Stefan flow forces); but not electrophoresis. Accordingly, we consider only those FF/C scrubbers where particle removal from the gas is aided by temperature or vapor concentration gradients and particle growth is due to vapor condensation. These effects can result from the cooling of a hot, humid gas by contact with cold liquid, the condensation of injected steam, or other means.

Several studies of scrubber operation where particle collection was enhanced by vapor condensation have been reported. Some investigations of the FF/C phenomena in particulate scrubbers have been made but the results have been either of qualitative nature or provided limited quantitative information applicable only to specific cases. Nothing adequate for the design of optimum industrial scale FF/C scrubbing system was found in the literature.

A systematic developmental study of FF/C scrubbing was started at Air Pollution Technology, Inc., under a previous contract, No. 68-02-0256, where the technical and economic feasibilities of applying FF/C scrubbing for fine particle collection were established. This study included

theoretical development of design equations for FF/C scrubbers. A limited bench scale experimental study was also performed to examine critical areas of application of these equations. The bench scale experimental study was extended further under Contract No. 68-02-0285 to evaluate multiple stage FF/C scrubbing, as reported in Calvert and Jhaveri (1974). It was concluded that multiple stage or continuous contact type scrubbers were most suitable for FF/C scrubbing application.

The purpose of the present study was to evaluate technical and economic feasibilities of FF/C scrubbing through an experimental study of a laboratory pilot scale FF/C scrubber. Based on the available information, a horizontal spray FF/C scrubber was selected. It was also important to evaluate the effects of scrubber operating parameters so that the region of optimum FF/C scrubber operation could be defined. To establish the economic feasibility, the operating costs were compared with high energy scrubbers and a case study was made to compare the economics of FF/C scrubbing system against high energy alternatives designed to control gray iron cupola emissions.

CHAPTER 2

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

SUMMARY

Flux force and water vapor condensation effects have the potential to greatly improve the collection efficiencies of low energy scrubbers for fine particles. The object of the research reported here was to corroborate the limited experimental and theoretical evidence of the feasibility of FF/C scrubbing by conducting a detailed experimental study of a laboratory pilot scale (14 to 28 m^3/min or 500 to 1,000 CFM) FF/C scrubber.

The economic feasibility of FF/C scrubbing was also evaluated during this study. The results define the range of emission properties for which FF/C scrubbing is determined to be economical. In general, FF/C scrubbing should be considered when high removal efficiencies are desired for fine particulate emissions; and the flue gas enthalpy is higher than 100 Kcal/Kg or spent steam is available in the plant. These conditions are common for industrial combustion processes, which include several major stationary pollution sources in the United States. The Midwest Research Institute Report (1971) ranks sources based on the total tonnage of particulates emitted annually.

Table 2-1 lists industrial sources of particulate pollutants ranked among the top fifteen in the nation in the M.R.I. Report (1971). Emission properties of these sources are favorably suited for the application of FF/C scrubbing. The annual emissions listed were determined by subtracting the amount of emissions removed in the existing control equipment from the total emissions. The "net control" listed is the product of the average efficiency of control devices and the application of the control devices for the industrial

Table 2-1. MAJOR INDUSTRIAL PARTICULATE SOURCES FOR WHICH FF/C SCRUBBING IS ATTRACTIVE

NOTE: The following information was taken from the Midwest Research Institute Report (1971). The source number (Roman numeral) refers to its rank in the U.S. as an industrial particulate pollution source.

SOURCE	ANNUAL PRODUCTION	NET CONTROL FRACTION	EMISSIONS MKg/yr
IV. IRON AND STEEL			
A. Sinter Plants (Sintering process)	46,300,000 MKg of Sinter	0.90	46,300
B. Coke Manufacture	81,600,000 MKg of Coal	0	81,600
1. By-Product	82,800,000 MKg of Coal	---	19,000
2. Pushing & Quenching	80,600,000 MKg of Iron	.99	52,600
C. Blast Furnace		.40	306,000
D. Steel Furnaces	59,700,000 MKg of Steel	.99	9,000
1. Open Hearth	43,500,000 MKg of Steel	.78	16,300
2. Basic Oxygen	15,200,000 MKg of Steel	.68	57,200
3. Electric Arc	118,800,000 MKg of Steel		
E. Scarfing		0	120,000
VI. FOREST PRODUCTS			
A. Wigwam Burners	24,900,000 MKg of Waste		
B. Pulp Mills	22,000,000 MKg of Pulp		
1. Kraft Process		.91	149,000
a. Recovery Furnace		.94	29,900
b. Lime Kilns		.30	38,100
c. Dissolving Tanks	2,300,000 MKg of Pulp	.91	9,000
2. Sulfite Process	756,000 MKg of Pulp		
(Recovery Furnace)	3,200,000 MKg of Pulp	.91	900
3. NSSC Process	1,100,000 MKg of Pulp	.70	38,100
a. Recovery Furnace	470,000 MKg of Pulp	---	74,400
b. Fluid-Bed Reactor	---		
4. Bark Boilers			

TABLE 2-1 (Continued)

SOURCE	ANNUAL PRODUCTION	NET CONTROL FRACTION	EMISSIONS MKg/yr
VII. LIME			
A. Rotary Kilns	14,700,000 MKg of Lime	0.81	267,000
B. Vertical Kilns	1,600,000 MKg of Lime	.39	3,600
VIII. PRIMARY NONFERROUS METALS			
A. Aluminum	5,300,000 MKg of Aluminum	.90	52,600
1. Calcining of Hydroxide	730,000 MKg of Aluminum	.40	31,700
2. Reduction Cells			
a. H. S. Soderberg	640,000 MKg of Aluminum	.64	9,000
b. V. S. Soderberg	1,600,000 MKg of Aluminum	.64	18,100
c. Prebake			
B. Copper	520,000 MKg of Copper	.85	6,000
1. Roasting	1,300,000 MKg of Copper	.81	25,400
2. Reverb. Furnace	1,300,000 MKg of Copper	.81	29,900
3. Converters			
C. Zinc	690,000 MKg of Zinc	.98	13,600
1. Roasting			
a. Fluid-Bed	138,000 MKg of Zinc	.85	3,600
b. Ropp, multi-hearth	560,000 MKg of Zinc	.95	2,700
2. Sintering	560,000 MKg of Zinc	---	13,600
3. Distillation			
D. Lead	420,000 MKg of Lead	.86	15,400
1. Sintering	420,000 MKg of Lead	.83	9,000
2. Blast Furnace	420,000 MKg of Lead	.50	1,800
3. Dross Reverb. Furnace			
XI. ASPHALT	228,000,000 MKg of Material		
A. Paving Material		.96	150,000
1. Dryers		.96	36,300
2. Secondary Sources			

TABLE 2-1 (Continued)

SOURCE	ANNUAL PRODUCTION	NET CONTROL FRACTION	EMISSIONS MKg/yr
B. Roofing Material	5,680,000 MKg of Asphalt	0.50	2,700
1. Blowing		---	12,700
2. Saturator			
XII. FERROALLOYS			
A. Blast Furnace	540,000 MKg of Ferroalloy	.99	900
B. Electric Furnace	1,900,000 MKg of Ferroalloy	.40	140,000
XIII. IRON FOUNDRY			
A. Furnaces	16,000,000 MKg of Hot Metal	.27	95,300
XIV. SECONDARY NONFERROUS METALS			
A. Copper			
1. Material Preparation	270,000 MKg Insulated Wire	0	37,200
a. Wire Burning	58,000 MKg of Scrap	.19	--
b. Sweating Furnaces	260,000 MKg of Scrap	.68	1,800
c. Blast Furnaces	1,100,000 MKg of Scrap	.57	15,400
2. Smelting & Refining			
B. Aluminum	450,000 MKg of Scrap	.19	5,400
1. Sweating Furnaces	920,000 MKg of Scrap	.57	900
2. Refining Furnaces	120,000 MKg of Cl Used	.25	46,300
3. Chlorine Fluxing			
C. Lead	48,000 MKg of Scrap	.90	--
1. Pot Furnaces	108,000 MKg of Scrap	.90	900
2. Blast Furnaces	500,000 MKg of Scrap	.90	2,700
3. Reverb. Furnaces			
D. Zinc	47,000 MKg of Scrap	.19	--
1. Sweating Furnaces	190,000 MKg of Scrap	.19	2,700
a. Metallic Scrap	210,000 MKg Zn Recovered	.57	1,800
b. Residual Scrap			
2. Distillation Furnace			

category. The information and ranks were taken from the M.R.I. report (1971). It is clear from Table 2-1 that FF/C scrubbing is a feasible and attractive particulate control method for several major industrial sources.

Experimental Program

Based on results from our previous studies, spray FF/C scrubbing configurations were selected for the experimental study. Test aerosol with titanium dioxide particles were generated in the laboratory by dry dispersing the respective pigment powders. Gas heating and steam were used to precondition the scrubber gas to the desired experimental conditions. A force draft cooling tower was used to cool the recirculating scrubber water.

Effects of several operating parameters were studied during the experiment. In general, particle collection in the FF/C scrubbers was higher as the amount of vapor condensed per unit of gas scrubbed (condensation ratio) was increased or the inlet particle number concentration was decreased.

Operating parameters besides the condensation ratio and inlet particle number concentrations which were studied for the spray FF/C scrubber are: The effect of the spray drop size, the effect of decreasing cooling water requirement, the mode of overall gas-liquid contact and the scrubber inlet liquid flowrate. The scrubber performance was better when the size of sprayed drops was smaller and when the amount of cold water sprayed in was higher for the same condensation ratio. The performance was also better when the scrubber inlet gas was exposed to the colder water spray first, resulting in the maximum temperature and vapor pressure gradients.

A mathematical model for the FF/C spray scrubber based on the unit mechanism approach gave only partial agreement with the experiment. Performance for cold gas without FF/C phenomena benefits was compared with a mathematical model based on accounting for collection by single drops as they decelerate after leaving the spray nozzle. The correlation was good for particles

of about 1.0 μmA diameter. However, experimental efficiencies were higher for smaller particles, possibly because of particle collection on the back of drops. Experimental efficiencies were lower for the collection of larger particles, possibly indicating lower utilization of sprayed liquid, higher drop coalescence and gas channeling. Design equations were developed empirically to represent the experimental results, and to be used for scale-up and design of industrial FF/C scrubbing systems with similar spray configuration.

Costs

Operating costs of a FF/C scrubber were compared to those of a high energy scrubber capable of equal performance. The costs of electrical power at $0.03 KWH, purchased steam at $6.40/MKg and recirculating cooling water at $0.9/MKg were used for this comparison. The results indicate that when high fine particle collection efficiencies are required or when the gas to be scrubbed is hot or humid, FF/C scrubbing is economically more attractive than high energy scrubbers.

In an earlier report, Calvert et al. (1973) evaluated the economic feasibility of FF/C scrubbing compared to other alternatives for two industrial sources. Based on the additional information on the performance of FF/C scrubbing obtained from this research, the economics of an FF/C system for a gray iron cupola were estimated. Good cost and performance data for a high energy (H.E.) scrubber on a cupola were available from another study and provided a basis for comparison. Capital investment requirements for the two systems are roughly the same but the H.E. scrubber costs about 70% more than the FF/C system for all annual operation expenses except labor, maintenance, liquid treatment, and solid waste disposal. Most of the cost advantage of FF/C scrubbing is due to a $63,500/yr higher power cost for H.E. scrubbing.

CONCLUSIONS

The following conclusions can be drawn from the results of this study:

1. The experimental study confirmed previous predictions of the technical feasibility of FF/C scrubbing. High collection efficiencies (>95%) for fine particles can be achieved with a condensation ratio of about 0.15 g vapor condensed/g dry gas, in a FF/C scrubber.
2. Of the several mechanisms involved in FF/C scrubbers, diffusiophoresis and inertial impaction enhancement by particle growth, which are practically independent of particle size, are the most important for fine particle collection. Thus, the condensation ratio and inlet particle number are significant operating parameters for FF/C scrubbing.
3. Effects of other operating parameters, such as the gas and liquid flowrates and contact scheme, on the performance of the FF/C scrubber have been experimentally studied. The results can be used to design the optimum FF/C scrubbing system depending on the specific properties of the industrial pollution sources.
4. Based on the experimental data, mathematical models and empirical design equations are described and can be used to scale-up similar FF/C scrubbers for industrial applications.
5. Based on economic considerations, the most favorable situations for the application of FF/C scrubbing are: (i) enthalpy of vaporization is available from the gas to be cleaned, (ii) high collection efficiencies are required for fine particles, and (iii) when future capacity expansion is anticipated. The smaller the size of the particles to be scrubbed, the more economically attractive FF/C scrubbing will look. These conclusions are illustrated by a case study of an economic comparison of FF/C and high energy scrubbing systems for a gray iron cupola.

RECOMMENDATIONS

The laboratory pilot scale experimental study reported here has established the technical and economic feasibility of FF/C scrubbing. Engineering design equations for the spray scrubber are also described. The following research and developmental program is recommended:

1. Experimentally demonstrate the feasibility of FF/C scrubbing on selected industrial sources. Pilot scale systems with capacities to scrub from 2.4 to 4.8 m^3/sec (5,000 to 10,000 CFM) should be used for demonstration. Problem industrial sources with fine particulate emissions and hot or humid flue gas should be selected for the demonstration. The FF/C scrubbing systems should be designed to operate at the optimum conditions with flexibility to account for process changes. These demonstration programs, for three industrial sources: a glass furnace, a secondary non-ferrous metal recovery furnace, a foundry cupola, are detailed in the report.
2. Theoretical and experimental evaluation of other scrubbing configurations, such as a mobile bed (TCA) scrubber should be made to determine the best configuration applicable to FF/C scrubbing systems.
3. Evaporative cooling of scrubber liquid containing suspended and dissolved solids is critical for the economic feasibility of FF/C scrubbing. The cooling towers generally available use packing which are susceptible to scaling by the solids. A different configuration, such as using sprays instead of the packings, may be more applicable. Experimental development of the cooling towers on a laboratory and subsequently on an industrial pilot scale is clearly warranted.
4. Theoretical and experimental study of the spray utilization, heat and mass transfer in gas-liquid systems, the nucleation of condensation and other matters which

significantly influence FF/C mechanisms should be made in order to resolve the present areas of uncertainty.

CHAPTER 3

BACKGROUND

Flux force effects on particles have been known for many years and the background is reviewed and discussed in depth by authors such as Waldmann and Schmitt (1966), Goldsmith and May (1966), Hidy and Brock (1970) and Calvert et al. (1972). The studies reported by these authors include both theoretical and experimental work. The experimental systems were designed so as to be readily definable and were much simpler than a scrubber in terms of the number of phenomena and the unsteady conditions involved.

Several studies of scrubber operation have also been reported where particle collection was enhanced by vapor condensation, such as Schauer (1951) and Lapple and Kamack (1955). However, systematic studies of the effects of FF/C phenomena were attempted only recently. Rozen and Kostin (1967) studied the collection of fine oil mist in a perforated plate column under controlled conditions of vapor condensation. They found that their results could be represented by an empirical equation relating the particle penetration, "Pt", with the mass of steam condensed per gram of inlet particles, "q_m" as:

$$Pt = 12.5\ q_m^{-0.56} \qquad (3\text{-}1)$$

A study of steam injection into a laboratory scale scrubber was carried out by Lancaster and Strauss (1971). They measured an increase in particle collection efficiency which was in direct proportion to the amount of steam injected rather than the amount of vapor condensed. They concluded that the increase in collection efficiency was due to particle growth.

Calvert et al. (1973) presents a detailed description

of the previously reported studies on FF/C scrubbing. Technical feasibility of FF/C scrubbing was established in this report, based on theoretical development of FF/C scrubber performance models and limited bench scale experimental work. Further bench scale experimental work, reported by Calvert and Jhaveri (1974) led to the following conclusions:

1. Diffusiophoresis and inertial impaction enhanced by particle growth are the most significant particle collection mechanisms in FF/C scrubbers, while thermophoresis has a minor effect. All of these mechanisms are practically independent of the particle size.
2. Performance of an FF/C scrubber depends heavily on the amount of vapor available for condensation and the number concentration of particles.
3. Multiple stage or continuous contact type of scrubbers are most suitable for FF/C application. They can be readily adapted to provide different conditions and geometry along the gas path to accommodate changing flowrates and particle concentrations.
4. The most critical assumptions for the application of FF/C scrubber engineering design equations are the specific details of heat and mass transfer, mode of gas-liquid contact and nucleation of condensation on the particles. For a higher ratio of gas phase mass transfer coefficient to the liquid phase heat transfer coefficient, better particle collection would generally be obtained.

Based on the above information, a spray scrubber configuration was selected for experimental study. The spray FF/C scrubber has the benefit of a lower energy requirement and lower capital costs than other low energy scrubbers because a higher gas velocity is permissible with the spray scrubber.

The following parameters were determined to affect the important particle collection mechanisms (diffusiophoresis and inertial impaction enhanced by particle growth) most signifi-

cantly:

a. Condensation ratio
b. Particle number concentration
c. Spray drop diameter
d. Cold liquid flowrate
e. Overall gas-liquid contact mode
f. L/G

Effects of these parameters on scrubber performance were experimentally evaluated in this study.

CHAPTER 4

EXPERIMENTAL PILOT PLANT

Based on the theoretical considerations described in the previous section, a horizontal spray scrubber was selected for the study of FF/C scrubbing on a pilot-plant scale. During this study, fractional penetrations of fine particles through the scrubber were experimentally determined for several scrubber operating conditions. In this section, the following information is described for the FF/C scrubber system:

1. Details of the pilot-scale scrubber system.
2. Scrubber operating procedures.
3. Particulate sampling procedures.
4. Methods of data analyses and calculation.
5. Accuracy of measurements.
6. Operational conditions studied.

THE SPRAY FF/C SCRUBBER

Pilot Scale Scrubber System

The schematic process flow diagram of the FF/C scrubber system is shown in Figure 4-1. Components of the scrubber system are listed in Table 4-1. The scrubber had a design capacity of 0.47 actual m^3/s (1,000 ACFM) inlet gas flowrate. As an illustration, flowrates in the lines shown in Figure 4-1 are described in Table 4-2 when the inlet stream to the scrubber is at 77°C, saturated with water vapor. The FF/C scrubber and the particle generator are described below.

FF/C Scrubber

Scrubber shell: 76.2 cm diameter x 3.8 m long made from "Techite" fiber glass reinforced plastic sewer pipe, with removable end flanges.

Spray arrangement: The scrubber consisted of three sections, with a spray nozzle manifold in each section. Each manifold had a capacity to spray 1.3 ℓ/s of liquid with a

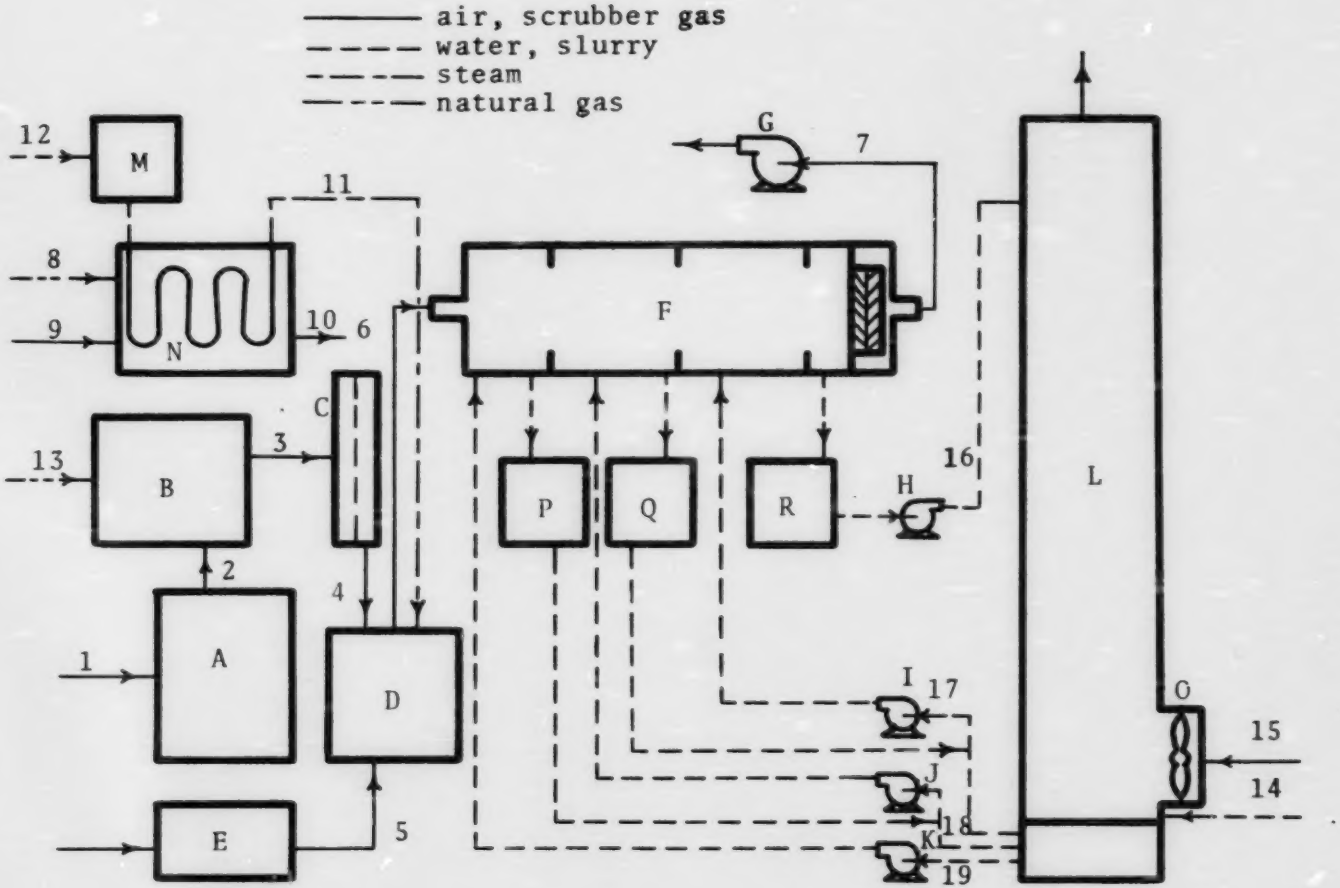


Figure 4-1. Process flow sheet for the FF/C spray scrubbing system.

Table 4-1. EQUIPMENT SPECIFICATIONS

A. AIR PREFILTER
(four automobile air filters with a capacity of 8.5 m^3/min air each)

B. AIR HEATER
(gas-fired air heater to heat air from 24°C to 100°C.

C. "ABSOLUTE" AIR FILTER
(MSA 'Ultra-Air' filter with a capacity of 0.476 m^3/s of air)

D. AIR, PARTICULATES AND STEAM MIXER
(disc and donut type mixer, 0.25 s residence time)

E. PARTICLE GENERATOR
(to generate dry dispersed solid particulates with a mass mean diameter less than 2 μmA, up to 10^9 particles/cm^3 of scrubber inlet air)

F. FF/C SCRUBBER
(horizontal spray scrubber with a mesh type mist eliminator)

G. SCRUBBER EXHAUST FAN
(centrifugal fan with design capacity of 0.476 m^3/s and ΔP of 50 cm W.C.)

H. PUMP
(227 ℓ/min and 15 m head; 80 GPM and 50 ft head)

I,J,K. PUMPS
(114 ℓ/min and 3.4 atm head each; 30 GPM and 50 psi each)

L. WATER COOLING TOWER
(a splash type, forced draft cooling tower; cooling range 47°C at 190 ℓ/min)

M. BOILER WATER TREATMENT
(11.3 ℓ/min ion exchanger)

N. STEAM BOILER
(760 kg/hr steam at 2.0 atm)

O. COOLING TOWER FAN
(4.25 m^3/s and 2.5 cm W.C. head)

P,Q. INTERSTAGE LIQUOR HOLDING TANKS
(200 ℓ capacity each)

R. SCRUBBER LIQUOR HOLDING TANK
(450 ℓ capacity)

SCRUBBER LIQUOR CIRCUIT
3.8 cm nominal diameter pipes, fittings, connections and valves

STEAM CIRCUIT
5 cm, 3.8 cm and 2.5 cm diameter pipes, connectors, valves, steam traps; 15.2 cm mist eliminator— all insulated

SCRUBBER GAS DUCTING
15 cm diameter inlet duct with connectors, insulated. 15 cm diameter outlet duct with connectors, insulated from scrubber outlet to sampling ports

Table 4-2. STREAM FLOW RATES OF THE SPRAY SCRUBBING SYSTEM

Stream No.	Compositions	Temp. °C	Vol. Flow		Mass Flow Kg/hr	Enthalpy* Kcal/Kg
			m^3/sec	ℓ/sec		
1 & 2	0.024 mole H_2O/mole dry air, air mixture	29	0.258	-	1,028	9.65
3 & 4	" "	100	0.306	-	1,028	42.5
6	0.696 mole H_2O/mole dry air, air mixture	77	0.480	-	1,450	206
7	0.0483 mole H_2O/mole dry air, air mixture	32	0.264	-	1,060	26.8
8	0.00675 mole H_2O/mole dry air, air mixture	29	0.112	-	442.8	9.65
9	Natural gas	29	0.009	-	71.2	-
10	0.154 mole H_2O/mole dry air, air mixture	232	0.208	-	514	190
11	Steam	106	-	-	442	644
12	City water	24	-	0.142	509	24
13	Natural gas	29	-	-	9.6	-
14	City water	24	-	-	26.8	24
15	0.00675 mole H_2O/mole dry air, air mixture	29	4.75	-	19,800	9.65
16	Process water	51	-	3.95	13,975	51
17	" "	20	-	1.20	4,525	20
18	" "	20	-	1.20	4,525	20
19	" "	20	-	1.20	4,525	20

*Air or Water

sauter mean drop diameter of 400 μm. The nozzles were located in a grid pattern on the manifolds to obtain a uniform distribution of spray in the scrubber cross-section. The liquid was sprayed co-current in the direction of gas flow. Thirty-two size 1/4B3 "Whirljet" nozzles supplied by Spraying Systems Company were used on each manifold.

Liquid flow system: The system was specially designed so that the cold scrubber liquid from the cooling tower could be sprayed either through all of the three manifolds in the scrubber ("single stage"), or through either the first or the last manifold in the scrubber. In the last cases, the scrubber was operated as a three-stage scrubber by spraying the outlet liquid collected in one section of the scrubber, into the next section, and then into the third section in series. Thus, the cold liquid requirement was reduced to one-third of the amount when cold liquid was sprayed in all of the three sections. When the cold liquid was sprayed into the first section, the gas-liquid contact was co-current through the three sections and when it was sprayed in the last section, the contact was counter-current. Separation of sprayed liquid from one section to another was affected by sets of baffles, storage tanks, and pumps as shown in Figure 4-1.

Entrainment separator: A wire mesh entrainment separator, 38.1 cm diameter, 15.2 cm long, made from 0.28 mm stainless steel wire in a standard knit design with 98.2% voidage, was installed downstream of the third spray section.

Particle Generator

The test aerosol was generated by dispersing titanium dioxide pigment powders. The pigment was "Unitane OR-600", purchased from the American Cyanamid Company. The powder was sieved through a 16-mesh screen, fed by a screw feeder arrangement into a compressed air ejector, immediately downstream of a

0.64 cm orifice. The compressed air pressure upstream of the orifice was maintained at 1.0 atm, gage.

The feed rates of the powders were controlled, depending on the particle loading required. A cyclone and a multiple round jet impactor, both with cut diameters of 4 μmA, were used in series to remove coarse particles from the dispersed aerosols. Electrostatic charges on the dispersed particulates were neutralized with nine "Staticmaster" ionizing units supplied by Nuclear Products Company, with 500 microcuries of Polonium 210 in each. These units were located in the aerosol duct upstream of the mixing section.

Instrumentation and Calibration

The inlet gas flowrate was measured with a standard pitot tube located downstream of the air prefilter. Scrubber system liquor flowrates were measured by venturimeters and rotameters installed in the 3.8 cm piping. They were calibrated by measuring the weight of water flowing through the pipes in a given time, in the range of 0.5 to 1 ℓ/s. Error in the flowrate measurements was kept at less than ±0.2% of the flowrate by measuring at least 140 kg of water for each calibration point.

Temperatures in the scrubber system were measured by copper-constantan (type T) thermocouples. The thermoelectric voltages were recorded on a strip chart recorder equipped with a potentiometric amplifier. The thermocouples were calibrated against a standard mercury bulb thermometer using constant temperature baths and were found to correlate well with the standard E.M.F.-temperature relationships. Thus, the limits of error in measuring temperatures were ±0.8°C based on the manufacturer's specifications.

The scrubber gas line pressures were measured by U-tube, inclined and well-type manometers and "Magnehelic" pressure gauges. Pressure drops across the liquor venturimeters were measured with two-fluid (water and mercury) well-type manometers.

Moisture content in the inlet gas stream to the scrubber was measured by wet and dry bulb thermometers.

PARTICULATE SAMPLING SYSTEM

Two identical particle sampling trains were used to measure the particulate loadings and size distributions in the scrubber gas inlet and outlet streams simultaneously. The particulate properties were measured with cascade impactors, followed by Gelman type A glass fiber filters. The cascade impactors used were six and eight stage, non-viable Andersen samplers and two University of Washington, Mark IIIF in-stack impactors. The samples were collected on aluminum substrates coated with high vacuum silicone grease to prevent particle bounce. The particulate loadings were rechecked by sampling with the glass fiber filters only for each operating condition.

The sampling instruments, either the cascade impactors or the filter holders, were installed in the inlet and outlet ducts to minimize losses in the sampling probe. Sampling probe was a 1.3 cm diameter tube. 1.3 cm aluminum tubes were installed across the sampling instruments so that the sample flows could bypass the instruments in each train. The sample flowpaths were controlled with 3-way valves. Moisture from the sample gas was removed by three cold impingers and a silica gel dryer located downstream of the sampling instrument in each train.

The sampling probes, the sampling instruments and the aluminum tubing to the cold impingers were heated with insulated heating tapes controlled with variacs, to prevent water condensation in the lines. The dry gas sample flowrates were measured with a dry gas meter and a rotameter in each train. The sampling rates were controlled by valves on the high pressure and bypass lines of the oil-less vacuum pumps. Prior to each run, the sampling instruments were heated to the stack gas temperatures. The sampling lines were also heated and flushed by drawing gas through the bypass lines.

EXPERIMENTAL PROCEDURE

The auxiliary equipment and the measurement instrumentation were checked and started up prior to the start-up of the scrub-

ber. The liquor tanks were filled with city water and the boiler and cooling tower operations were started. The scrubber was started up by first starting the water flowrate and adjusting it to the experimental condition and then starting the scrubber blower to draw filtered ambient air through the scrubber. After a steady state was reached, the gas heater was fired and the air was heated up to the desired temperature. Then steam was introduced to attain the experimental moisture content in the gas stream. Again, after a steady state was reached, the particles were introduced to attain the experimental moisture content in the gas stream. Again, after a steady state was reached, the particles were introduced to attain the experimental operating condition. It normally took 60 to 90 minutes to attain the experimental condition.

The flowrates, temperatures, pressures, moisture contents and scrubber pressure drops were measured every time a steady state was attained during the above procedure. These parameters were also measured just before the start-up of particulate sampling, at least once during the sampling or every thirty minutes, and just after the sampling was completed. Sampling time in the scrubber inlet duct varied from 15 minutes to 60 minutes depending on the particulate loading and the sampling rate ranged from 0.68 to 1.0 m^3/hr at the probe. The outlet sampling time was from 2 to 3 times the inlet and the sampling rate was about twice the inlet sampling rate to allow for the lower outlet particle loadings.

When the total sampling time exceeded 30 minutes, the sampling was interrupted and the coarse particles caught in the cyclone and the impactor on the particle generator were cleaned out. This was necessary to maintain a steady performance of the particle generator. As the inlet and outlet ducts were sampled simultaneously, small variances in the particle generator performance did not significantly affect the results. Also, since at least 90% of the particles were smaller than 2 μm, the sampling rates were not adjusted to get isokinetic velocities at the probes.

The experimental conditions were found to stay very stable once a steady state was reached. For all the experimental runs reported, the temperature conditions for the experiment varied within ±1.5°C during the experimental period.

EXPERIMENTAL CONDITIONS STUDIED

During the experimental study, the scrubber performance was studied for five scrubber operational modes. The experimental runs for one of the operational modes, with cold water sprayed in all of the three sections of the scrubber, were repeated to check the reproducibility of results. The operating modes are described in Table 4-3. During each mode, scrubber performance was studied for a range of "q'", varying from the cold runs to q'=0.2.

METHODS OF ANALYSIS AND CALCULATION

As mentioned earlier, the particle characteristics and the scrubber performance were measured by sampling with absolute glass fiber filters and cascade impactors. Information on total particulate loadings and thus the overall scrubber penetrations, $\overline{Pt}$, was obtained from both of the above sampling apparatus. Sampling with the cascade impactors provided additional information on the particle size distributions, fractional loadings and thus the fractional penetrations, and the inlet particle number concentrations.

Particle Loadings and Overall Penetrations

The total particle loadings in the inlet and outlet ducts were calculated in the following manner:

1. The sample flowrate was converted to the standard conditions of 0°C and 76 cm of mercury pressure.
2. Total weight gain on the sampling elements was measured with an analytical balance, Sartorius Model 244, ±0.05 mg precision.
3. The particle mass loading, $c_p(g/DNm^3)$, was calculated from:

Table 4-3. SPRAY SCRUBBER OPERATION MODES

Dust used: Titanium dioxide, -16 mesh
$n_i \approx 10^6/cm^3$

NO.	OPERATING MODE	INLET LIQUID FLOWRATE PER SECTION (ℓ/s)	DROP SIZE
1	One Stage	~1.0	Small (Mass mean dia≈350 μm)
2	One Stage	~1.0	Small
3	One Stage	~0.76	Small
4	One Stage	~0.76	Large (Mass mean dia≈450 μm)
5	Three Stage Co-Current	~1.0	Small
6	Three Stage Counter-Current	~1.0	Small

NOTES:
1. No. 2 was a repetition of No. 1.
2. Liquid flow rate for No. 3 was reduced by reducing the number of spray nozzles.
3. Liquid flowrate for No. 4 was reduced by reducing the spray pressure.

$$c_p = \frac{\text{(Total weight gain, g)}}{\text{(Sampling rate, DNm}^3\text{/min)x(Sampling time, min)}} \qquad (4\text{-}1)$$

4. The overall penetration was calculated from:

$$\overline{Pt} = \frac{c_{po}}{c_{pi}} \qquad (4\text{-}2)$$

where "c_{po}" and "c_{pi}" were the outlet and inlet particle loadings measured simultaneously for the run.

Particle Size Distribution

The particle size distributions were measured gravimetrically using the cascade impactor data.

The particle diameter measured by an impactor is called "aerodynamic diameter" and it has the units of "aerodynamic microns, μmA." This is the effective diameter for particle separation by inertial impaction and it takes into account the effects of particle density and particle slip between gas molecules. Aerodynamic diameter is related to geometric diameter (actual size) by the following relationship:

$$d_{pa} = d_p \, (C' \, \rho_p)^{0.5} \qquad (4\text{-}3)$$

where d_{pa} = aerodynamic diameter, μmA ≡ μm $\sqrt{g/cm^3}$
d_p = actual diameter, μm
C' = Cunningham slip factor
ρ_p = particle density, g/cm³

The Cunningham slip factor is a complex function of the mean free path of the gas and the particle diameter. It increases as temperature increases and as pressure decreases. For air at standard temperature and pressure it is given approximately by:

$$C' = 1 + \frac{0.165}{d_p} \qquad (4\text{-}4)$$

The particles were assumed to have a log normal distribution. Cumulative mass of particles collected on a stage and all the stages below, including the absolute filter, were calculated as a percentage of the total weight gain. The cut diameters for the impactor stages were calculated from the sampling rate, based on the manufacturer's specifications. The geometric mass mean aerodynamic diameter, d_{pg}, and the geometric standard deviation, σ_g, of the size distribution were then determined from a plot of the aerodynamic cut diameters against the percent cumulative loading smaller than the cut diameters, on a log probability paper.

Particle Number Concentration

Particle size distribution as measured by cascade impactors was in terms of mass and it was necessary to convert this into a number distribution. For log-normal size distributions it is simple to determine number mean diameter from mass mean diameter but this does not provide information as to the number concentration. A method was developed for computing the number concentration by multiplying a hypothetical number concentration based on "d_{pg}" by a correction factor which is dependent on "σ_g". The derivation of this relationship is given below.

The total number concentration of particles, n_t, can be computed from:

$$\int_0^{v_t} \frac{dn}{dv}\, dv = n_t, \text{ no./cm}^3 \qquad (4\text{-}5)$$

and,

$$\frac{dn}{dv} = \frac{3}{4\,\pi\, r_p^3}, \frac{\text{number of particles}}{\text{cm}^3 \text{ of particles}} \qquad (4\text{-}6)$$

where n = cumulative particle number concentration, smaller than "r_p", no./cm^3

v_p = cumulative particle volume concentration, cm^3/cm^3

v_t = total particle volume concentration, cm^3/cm^3

r_p = particle radius, cm

We define $V \equiv \frac{v}{v_t}$ = cumulative volume fraction, dimensionless. And,

$$\int_0^{v_t} \frac{dn}{dv}\, dv = v_t \int_0^1 \frac{dn}{dv}\, dV \qquad (4\text{-}7)$$

The influence of particle radius can be related to the mass mean radius by:

$$R_{ni} \equiv \frac{\left(\frac{dn}{dv}\right)_i}{\left(\frac{dn}{dv}\right)_m} = \left(\frac{r_{pg}}{r_{pi}}\right)^3 \qquad (4\text{-}8)$$

where R_{ni} = ratio of actual number concentration for particle radius, r_{pi}, to hypothetical number concentration based on "r_{pg}", dimensionless

Subscript "i" is for radius "r_{pi}"

Subscript "m" is for mass mean radius "r_{pg}"

Thus, R_n, total number concentration ratio, is:

$$\int_0^1 R_{ni}\, dV = R_n = \frac{\text{actual number concentration}}{\text{no. concentration based on } r_{pg}} \qquad (4\text{-}9)$$

This equation was integrated numerically for different values of "σ_g". Note that for a log-normal distribution the probability of the ratio of size to mean size is normally distributed. Therefore, "R_N" is defined by "σ_g" only. A plot of "R_N" versus "σ_g" was thus obtained. From the total particulate loading and "d_{pg}" at scrubber inlet, the hypothetical number concentration was calculated for each run. Particle density of the titanium dioxide was assumed to be 3.0 g/cm^3. Then, using the experimental "σ_g", n_i, the particle number concentration at the scrubber inlet, was determined from the plot.

These values of "n_i" were checked periodically by using the Gardner and Pollack Condensation Nuclei Counters. The values were found to agree within a factor of 3.

Fractional Penetrations

The computation of penetration as a function of particle aerodynamic diameter, or the fractional penetration through the scrubber, was done by a stepwise graphical procedure. The procedure is based on the following equations:

Overall penetration can be defined as:

$$\overline{Pt} = \frac{1}{c_{pt}} \int_{o}^{c_p} Pt_{d_{pa}} \, dc_p \qquad (4\text{-}10)$$

where "c_{pt}" is the total particle loading and "$Pt_{d_{pa}}$" is the penetration for particle diameter, d_{pa}, and it is given by:

$$Pt_{d_{pa}} = \frac{f(d_{pa})_o}{f(d_{pa})_i} = \frac{\left[\frac{dc_p}{d(d_{pa})}\right]_o}{\left[\frac{dc_p}{d(d_{pa})}\right]_i} \qquad (4\text{-}11)$$

where $\left[\frac{dc_p}{d(d_{pa})}\right]$ is the slope of cumulative mass loading less than "d_{pa}" versus the aerodynamic particle diameter curve at "d_{pa}", and equals "$f(d_{pa})$".

Thus, to determine the fractional penetration, the following procedure was followed:

1. Cumulative mass loading for all the stages and the filter, below the stage with a cut diameter of "d_{pa}", was plotted against "d_{pa}" from the inlet and outlet cascade impactor samples.
2. Slopes of the inlet and outlet plots above were determined for several "d_{pa}" values in the range of 0.4 to 5 μmA. The fractional penetrations were then determined and plotted from the ratio of the slopes, as described above.

ACCURACY OF MEASUREMENT

Accuracy in measuring the particle size distributions, fractional penetrations, overall penetrations and the inlet particle number concentrations from the cascade impactor data depended on several factors. The precision of the balance, impactor handling procedures, and measurement of sampling rate influence the subsequent determination of cut diameters. Subjective judgments of the persons analyzing the data are involved when reading the graphs and determining slopes. It is beyond the scope of this study to determine the accuracy statistically. The best possible care was taken in the laboratory, sampling and analytical procedures to obtain accurate data and results. At least two runs were made at every operating condition to duplicate the data.

During the determination of overall penetrations using "absolute" glass fiber filters, at least 5 mg of sample were collected on each filter. Precision of the analytical balance was ±0.05 mg. Thus, the maximum error due to the weighing accuracy in determining $\overline{Pt}$ was $\overline{Pt} = \frac{c_{p_o}}{c_{p_i}}$. Thus:

$$\frac{d\overline{Pt}}{\overline{Pt}} = \frac{dc_{p_o}}{c_{p_o}} - \frac{dc_{p_i}}{c_{p_i}} \qquad (4\text{-}12)$$

As the absolute values of the error were small compared to the actual weights and as the error terms are additive:

$$\text{Maximum error, } \overline{Pt} = \frac{\Delta c_{p_o}}{c_{p_o}} + \frac{\Delta c_{p_i}}{c_{p_i}} \qquad (4\text{-}13)$$

$$= \pm \frac{0.2}{5} = \pm 4\%$$

CHAPTER 5

EXPERIMENTAL RESULTS AND DISCUSSIONS

Experimental and sampling procedures, and the methods of data analyses and calculation of results are described in the preceding chapter. During the experimental study, scrubber performances were determined as fractional penetration of particles (with respect to the aerodynamic particle diameter) and the overall particle penetration through the scrubbers. Since the scrubber inlet particle characteristics (size distribution and number concentration) were different for each run, the fractional penetrations provide a common base for comparing scrubber performances for different operating conditions. The scrubber operating conditions and performance are tabulated, with the fractional penetration plots for cascade impactor runs, in Appendix 1.

RESULTS

The spray scrubber was evaluated at five operating modes, as listed in Table 4-3. For each operating mode, the scrubber performance was measured for a range of "q'" values. Effects of the following variables were also determined:

1. The amount of cold water sprayed in the scrubber was varied. Effect of reducing the cold water spray in a 3:1 ratio was studied by operating the scrubber in a three-stage mode.
2. The L/G ratio was controlled by changing the inlet flowrate.
3. Liquid drop size distribution was changed at the same L/G ratio.
4. Overall gas-liquid contact mode was altered by operating the three stage scrubber in the co-current or counter-current mode.

As particle growth and diffusiophoresis are expected to contribute the most to the enhancement of particle capture in the scrubber, the effects of "q'" and "n_i" on "Pt" were determined. "Pt" for 1.0 μmA and 0.6 μmA particles are plotted against "q'" in Figures 5-1 through 5-6 for the operating modes studied. Data points on these plots were read from the fractional penetration plots in Appendix 1. The data points were found to be scattered, possibly indicating the effects of other parameters, such as "n_i" and the inlet liquid temperatures.

DISCUSSION

The spray scrubber performance is compared with the results of Lancaster and Strauss (1971) and with some plate scrubber data on Figure 5-7, a plot of particle penetration versus condensation or injection ratio, for 1.0 μmA particles. The following is surmised from the plot:

1. Particle penetration depends heavily on the condensation ratio, "q'". Calvert et al. (1973) have shown that "q'" is sufficient to define particle deposition rate, without regard to "n_i", if there is no condensation on the particles.
2. A comparison of curves 1 and 2 shows that the scrubber performance could be reproduced, if operated at nearly the same conditions, thus reinforcing the validity of experimental data and techniques.
3. A comparison of curves 1 or 2 and 3 indicates an apparent anomaly. The amount of water sprayed into the scrubber during runs indicated by curve 3 was about 25% less than that sprayed for the runs indicated by curves 1 and 2. Thus, curve 3 may be expected to have higher penetrations. This effect may be due to better liquid utilization when less water was sprayed in, resulting in a higher collection efficiency of large particles by impaction. (Note that particle growth is

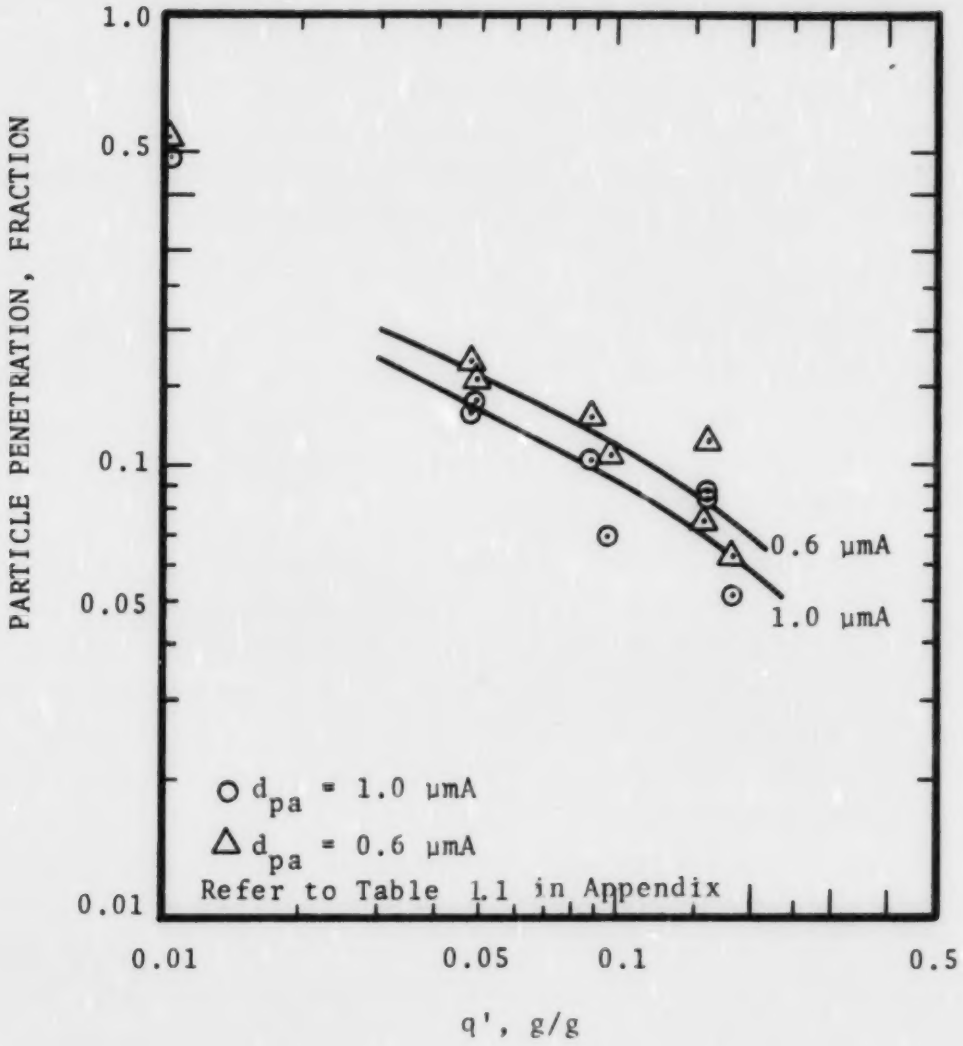


Figure 5-1 - Penetration versus condensation ratio one stage spray.

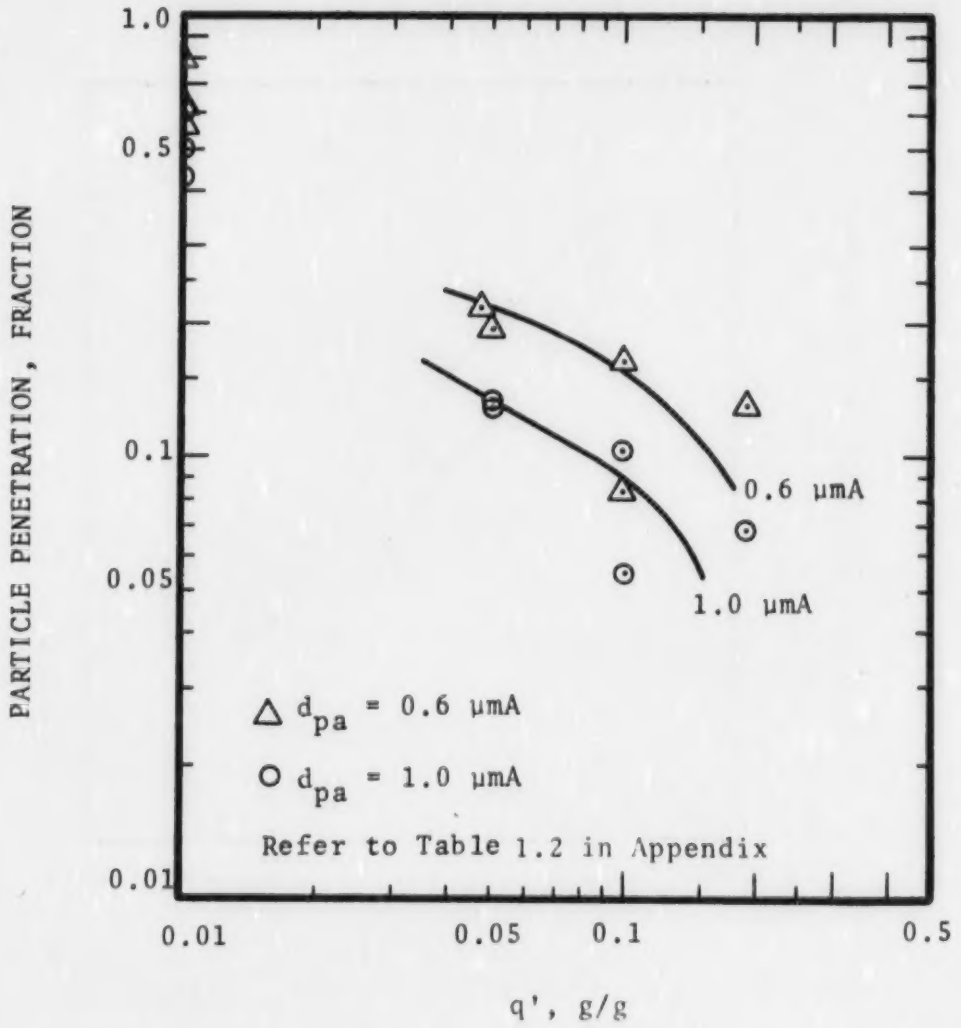


Figure 5-2 - Penetration versus condensation ratio, one stage spray.

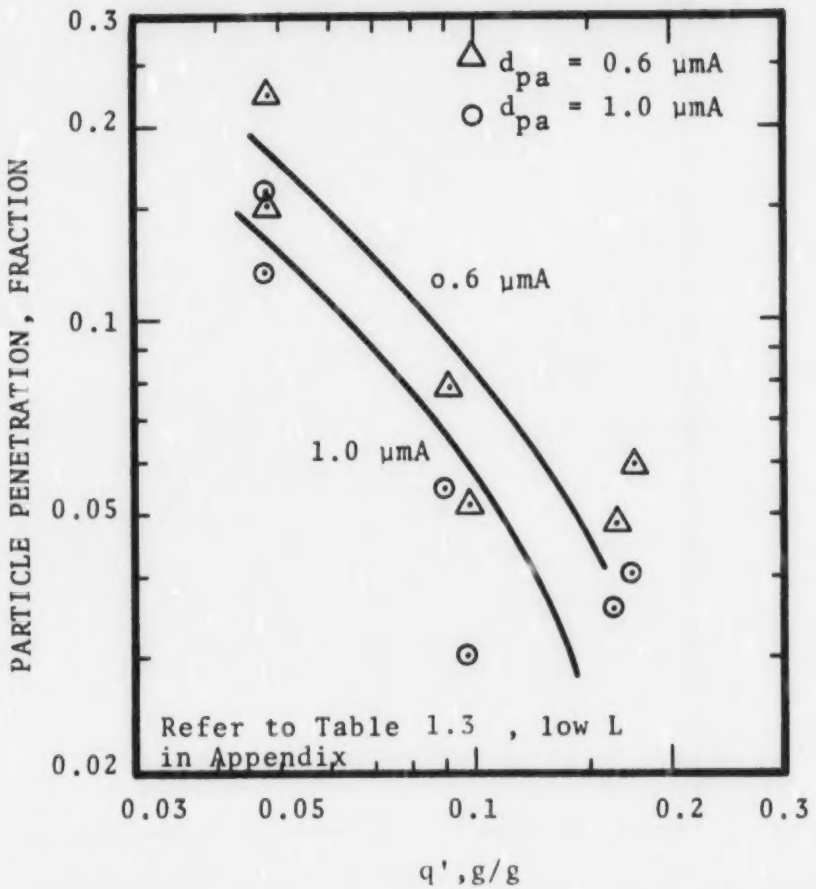


Figure 5-3 - Penetration versus condensation ratio, one stage spray.

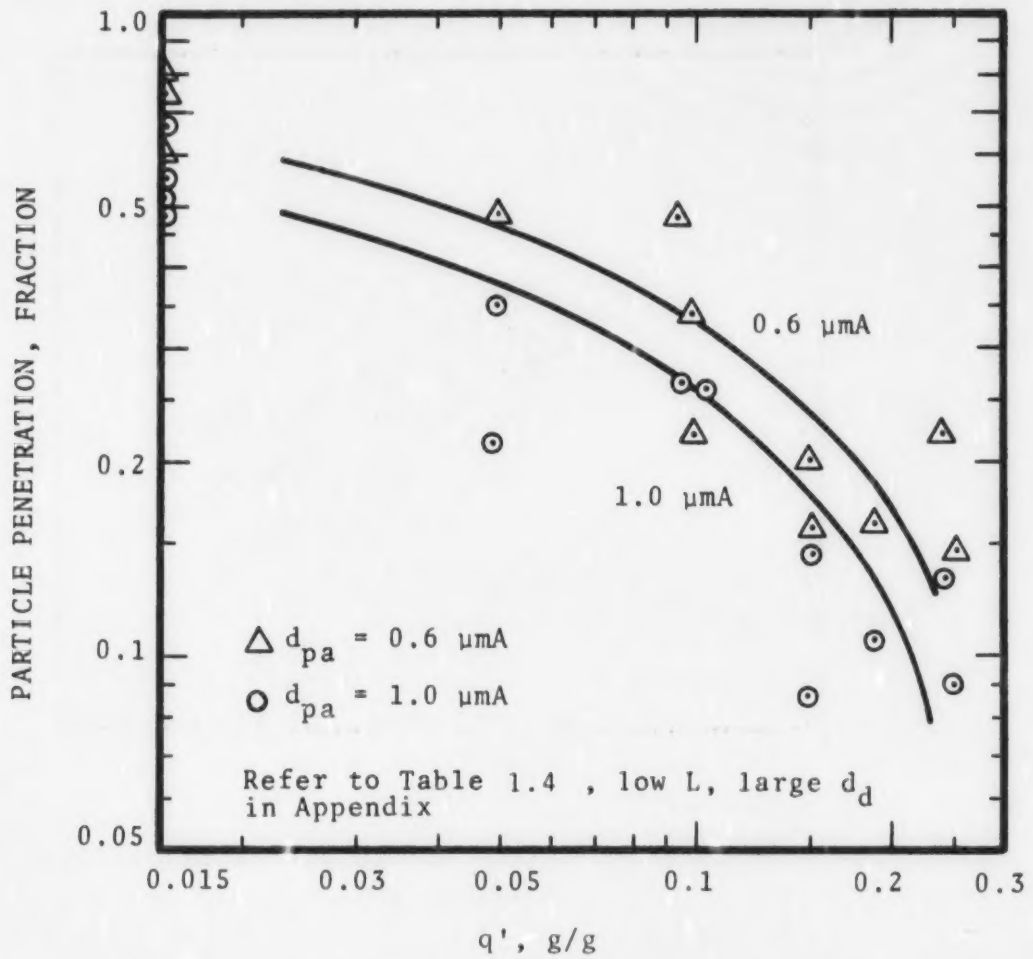


Figure 5-4 - Penetration versus condensation ratio, one stage spray.

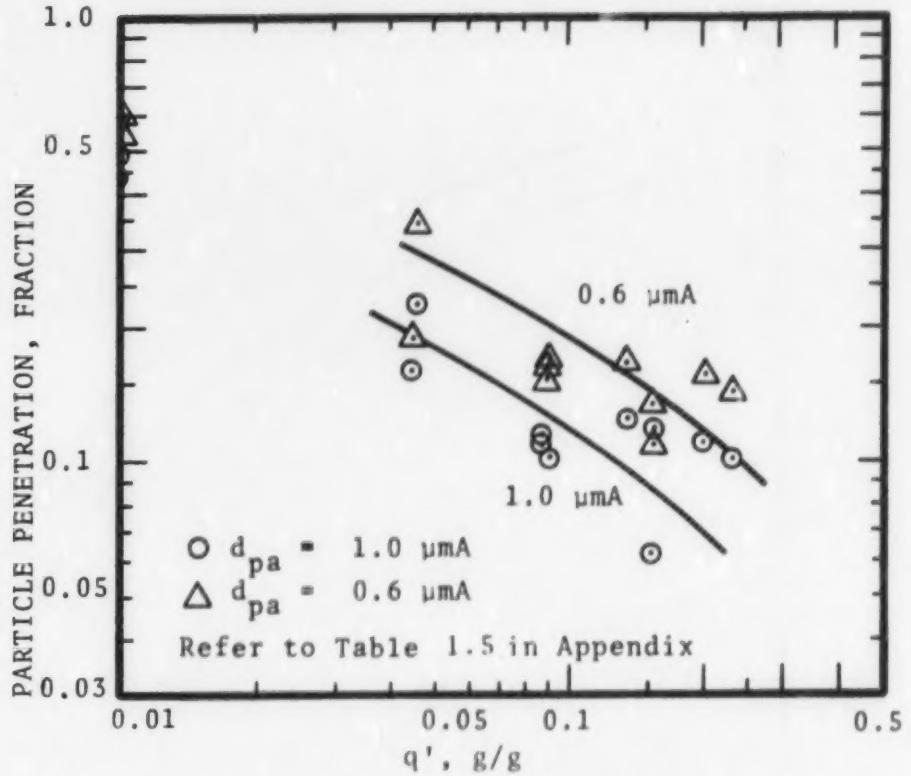


Figure 5-5 - Penetration versus condensation ratio, three stage co-current spray.

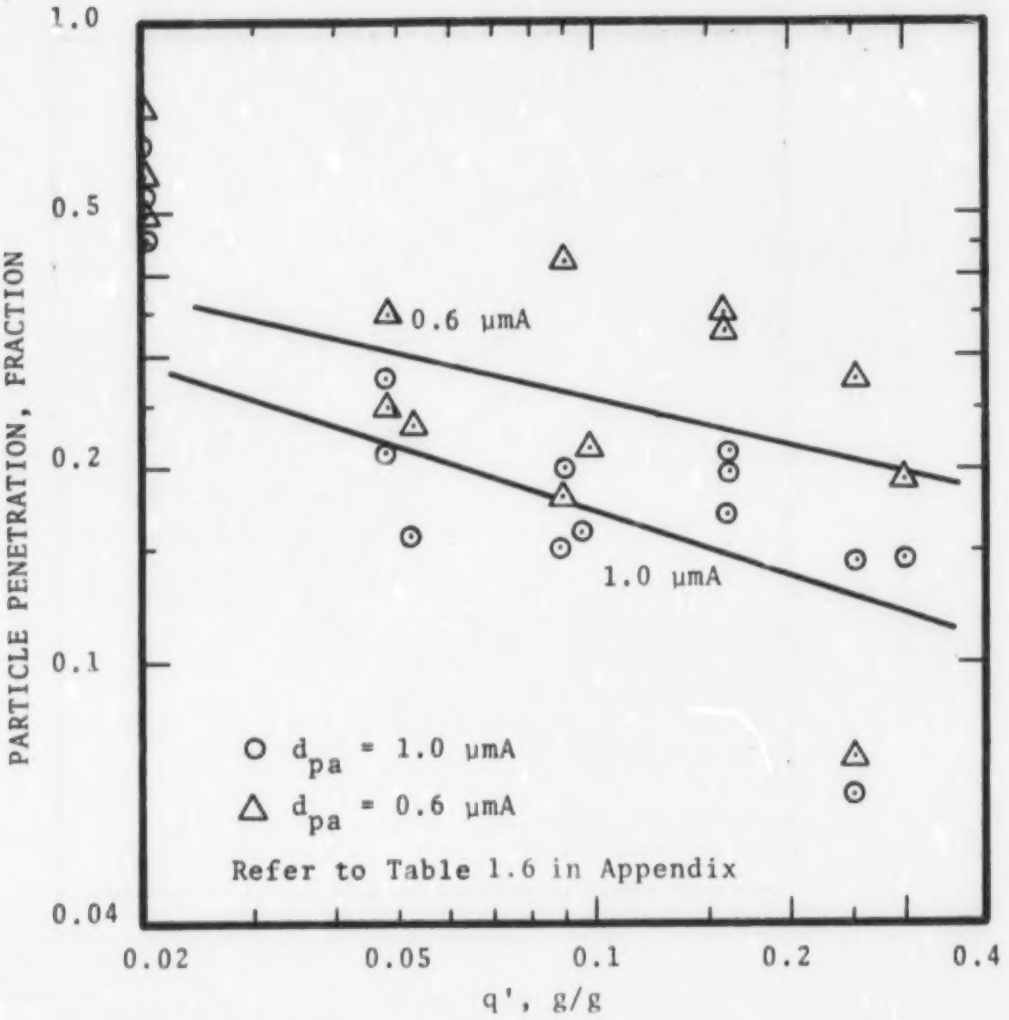


Figure 5-6 - Penetration versus condensation ratio, three stage counter-current spray.

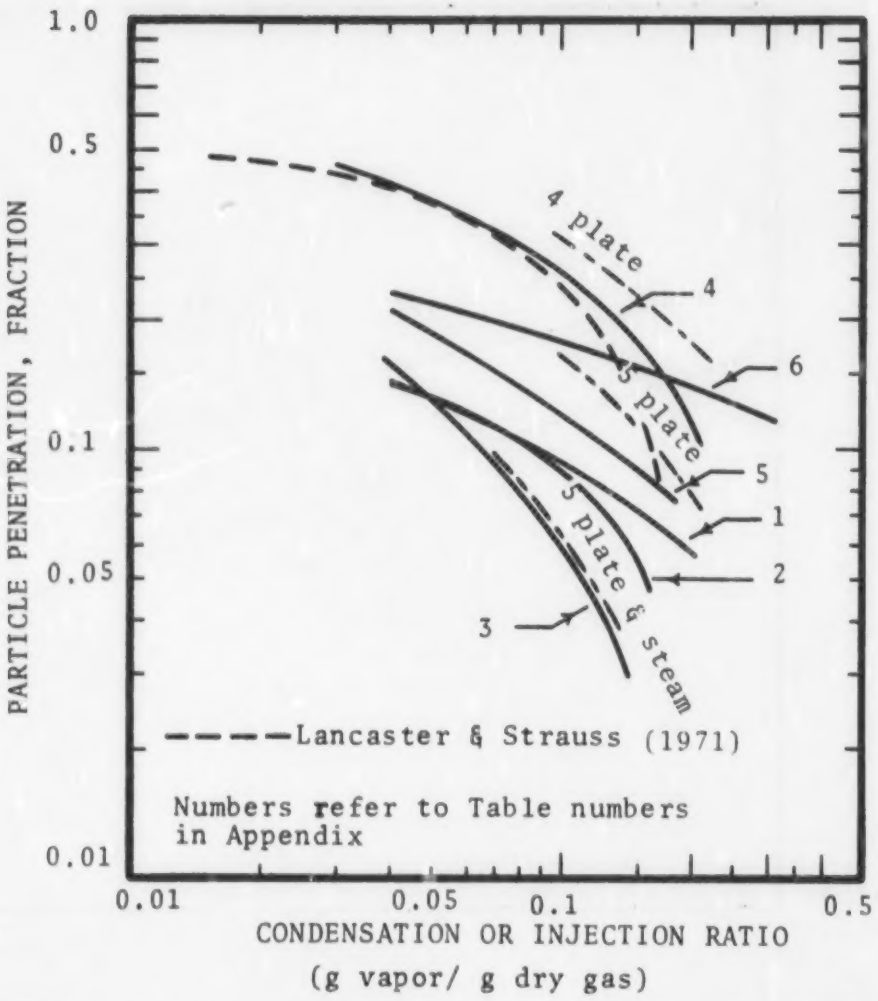


Figure 5-7 - Comparison of FF/C plate and spray scrubber results for 1 μmA particles

higher at higher "a'" values.) Spray drop diameters during all the runs were the same. The better liquid utilization may be due to less drop coalescense and lesser wall losses at the lower liquid flowrate. This effect bears further experimental investigation.

4. A comparison of curves 3 and 4 illustrates the effect of spray drop diameter. Although the liquid and gas flowrates were identical for these runs, the spray drop volume mean diameter for curve 4 was about 1-5 times the diameter for curve 3. Thus, the particle collection by impaction and the spray drop space density (number of drops in a unit scrubber volume) are lower for curve 4, resulting in the high penetrations.
5. A comparison of curves 1 or 2 (1 stage) with 5 (co-current), shows that the particle penetrations are higher when the amount of cold liquid sprayed is reduced by about 67% although the total liquid spray rate is the same. In both the operating modes cold liquid was sprayed in the section where the gas enthalpy and vapor content were highest. Thus, the highest possible temperature and vapor concentration gradients were imposed in this section. The slightly higher penetrations for curve 5 indicate that although most of the particle growth occurred in the first section of the scrubber, FF/C mechanisms were also effective in the second and third sections.
6. A comparison of curves 5 with 6 (counter-current) indicates the importance of causing particle growth quickly in a FF/C scrubber. The only difference in scrubber operation was that for curve 5, the coldest water was sprayed into the gas with the highest enthalpy and water vapor content; while for curve 6, the hottest water was sprayed into this gas in the first section, thus providing a more uniform distribution of gradients along

the length of the scrubber. Curve 5 penetrations are lower, probably due to more particle growth for co-current contacting.

CHAPTER 6

FF/C SCRUBBER PERFORMANCE PREDICTION METHODS

The prediction of particle collection performance for FF/C scrubbers in advance of experiments can be done by means of theoretically based mathematical models. The approach used is to derive particle collection equations which account for all of the applicable unit mechanisms, which could be active in the scrubber. Such models are then used to predict particle collection in the spray FF/C scrubbers. The predicted performances are compared to the experimental results.

Particle collection in the FF/C spray scrubber is affected by inertial impaction, diffusiophoresis, and thermoporesis. During this study our approach was to develop equations for particle collection by inertial impaction, and use them in conjunction with the mathematical models for particle growth and collection by flux forces as described by Calvert et al. (1973).

Particle collection efficiency by inertial impaction in a spray scrubber can be predicted by means of methods described in the "Scrubber Handbook" (Calvert et al. 1972), for cases where the drop velocity is constant, or may be considered so. When the spray is generated by high pressure nozzles, the drop velocity is initially very high compared to the terminal settling velocity. Therefore the collection efficiency of the drop decreases greatly as the drop slows down and the overall collection by the drop is the integrated effect of efficiency over the drop trajectory.

Walton and Woolcock (1960) studied this problem in connection with the use of pressure sprays to control coal mine dust. They computed the relationship between collection efficiency and the distance traveled by a drop for several particle sizes and drop diameters. Figure 6-1 is taken from their paper and shows these relationships as predicted for coal dust (density = 1.37 g/cm^3). Drop velocity is also plotted so that one can find

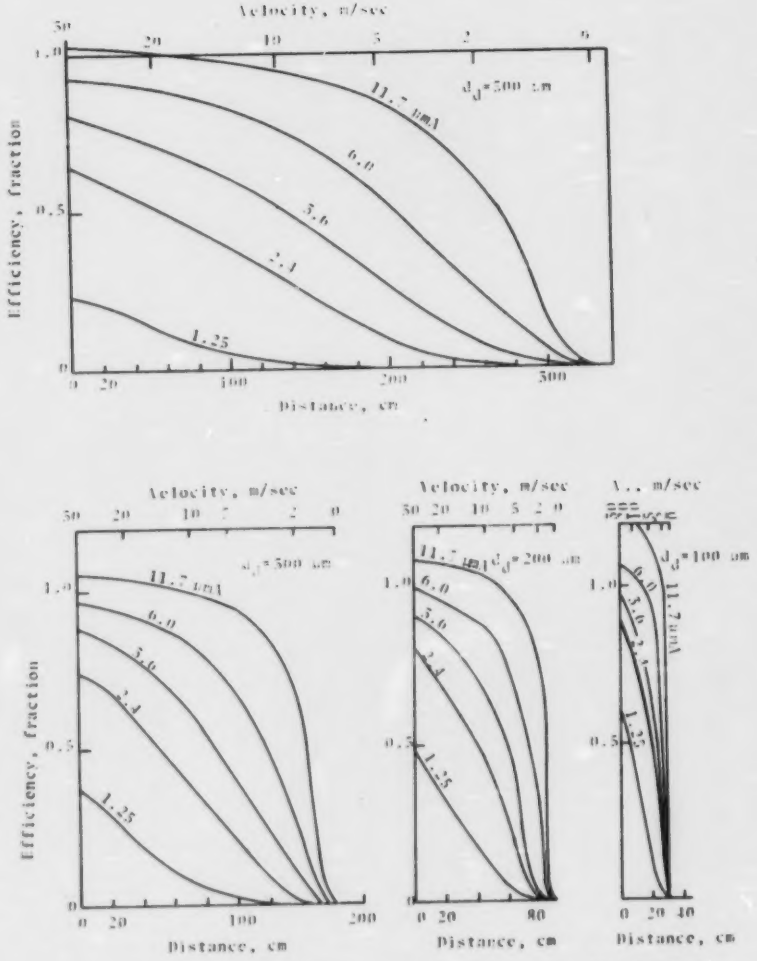


Figure 6-1 - Predicted particle collection efficiency for sprays by inertial impaction and interception

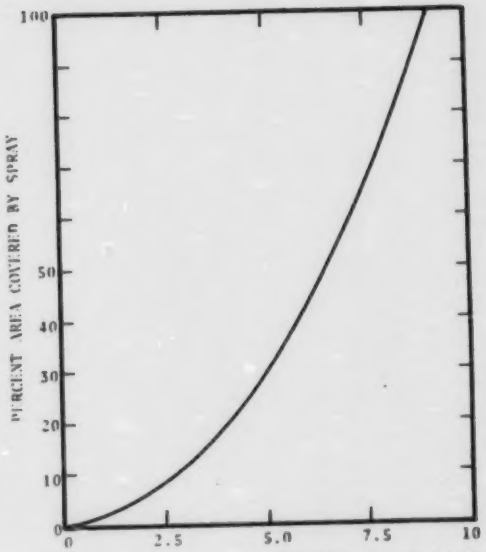


Figure 6-2 - Scrubber area covered by sprays.

efficiency as the drop accelerates from a given initial velocity.

The relationships given in Figure 6-1 can be used to predict the collection efficiency of a spray scrubber making the following assumptions which we used in our model:

1. Assume that the particle concentration is uniform as the aerosol enters a spray stage, that it decreases exponentially as it passes through the stage, and that it is completely mixed (i.e. uniform concentration) before entering the next stage.
2. Assume that collection is by inertial impaction on the front of the drop only. This is the same as Walton and Woolcock assumed.
3. Assume that the percent of the gas area covered by the sprays (co-current) varies as shown in Figure 6-2, which is based on the arrangement of nozzles used in our pilot plant spray scrubber.
4. Assume that the drop diameter is uniform.

Based on the above assumptions, the equations describing the multi-stage, co-current spray scrubber are as follows:

Volume of gas which is swept clean of particles per unit of liquid volume is:

$$V_s = \left(\frac{3}{4r_d}\right) R_d E \times 10^{-3}, \ (m^3/\ell) \qquad (6\text{-}1)$$

where

V_s = gas volume swept clean per liter of drops, m^3/ℓ
r_d = drop radius, cm
R_d = drop range (i.e., distance traveled), cm
E = average particle collection efficiency over range "R_d", fraction

If the collection of particles is a first order process,

$$Pt_\Delta = \exp - \left(V_s \frac{L}{G}\right) \qquad (6\text{-}2)$$

where L/G = Liquid to gas flow ratio, (ℓ H_2O/m^3 gas)

Pt_Δ = Penetration per stage for a given particle diameter, fraction

The penetration for "N" stages is:

$$Pt_N = (Pt_\Delta)^N \qquad (6\text{-}3)$$

The average efficiency was computed by plotting the product of efficiency times fraction of gas flow covered by sprays, versus the drop range (distance traveled) and then doing a graphical integration. These plots were made for several particle sizes and for an initial velocity of 20 m/sec and drop diameters of 0.05 cm and 0.03 cm. These conditions correspond to our pilot plant runs at 2.7 atm (40 psig) spray nozzle pressure. We also assumed that the maximum drop range is 100 cm, based on scrubber size.

The results of the computations for a liquid to gas ratio of 2.35 ℓ/m^3 (18 gal/MCF), corresponding to the flow rate per stage in our pilot plant runs, and for three stages are shown in Figure 6-3 for 0.05 cm drops and Figure 6-4 for 0.03 cm drops. Because of the difference in slope between the predictions and the experimental data we explored the influence of decreasing the amount of effective spray, assuming that there is agglomeration The results are shown in Figures 6-3 and 6-4.

As can be seen, the predictions are fairly close to the data at the cut diameter (0.5 Pt) but not for other particle diameters. We have not yet been able to devise a model that will account for this discrepancy. It is quite possible that lower penetration for particles smaller than 1.0 μmA is due to their collection on the backs of the drops. However, we do not yet have a predictive cor-

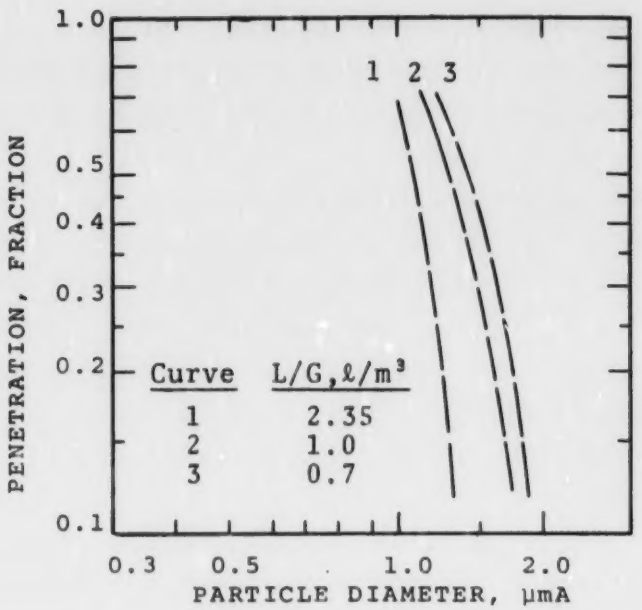


Figure 6-3. Spray scrubber penetration predictions for 500 μm drop diameter.

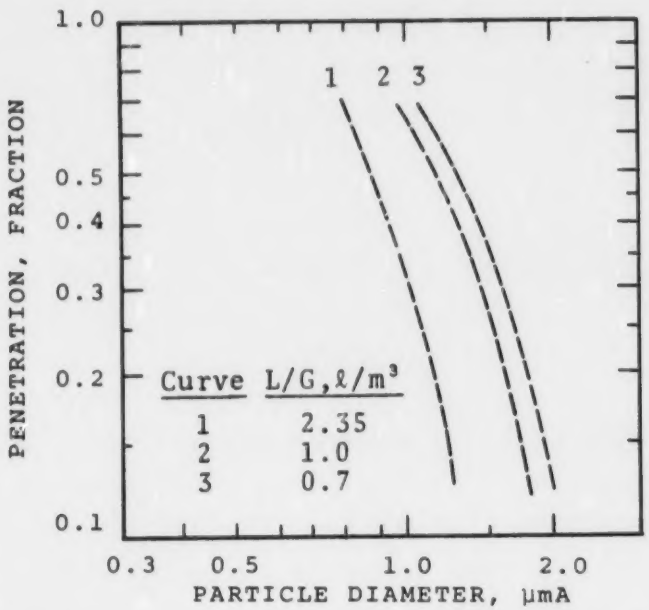


Figure 6-4. Spray scrubber penetration predictions for 300 μm drop diameter.

relation to account for this effect. Since a design equation for particle collection by inertial impaction could not be validated by our data, a model for FF/C spray scrubber was not developed.

In order to obtain design equations for scale-up purposes of FF/C spray scrubbers similar to the scrubber tested in this study, a curve fitting technique was used. Scrubber performance data for 1.0 μmA particles are plotted in Figures 6-5 through 6-7 , as particle penetration versus the amount of vapor condensed per particle, "q". This value was used instead of "q'"as it normalizes the effect of particle number concentration, "n_i". Again, scatter in the data was observed, possibly due to the effects of inlet liquid temperatures and the actual amount of vapor condensed on the particles. The range of scatter around the least square fit was within ±50%.

Curve fitting procedures were employed on each horizontal spray FF/C scrubber data set to obtain the functional relationship between "Pt" and "q". The initial step is the assumption that the relationship between "Pt" and "q" can be represented as a power function:

$$Pt = Aq^B \qquad (6\text{-}4)$$

or synonymously as the straight line equation:

$$\ln Pt = \ln A + B \ln q \qquad (6\text{-}5)$$

The method of least squares was utilized to obtain the best straight line curve fit through the experimental set of paired variables, "ln Pt" and "ln q", where "ln q" was regarded as an ordinary variable measured without appreciable error, and "ln Pt" as the random variable.

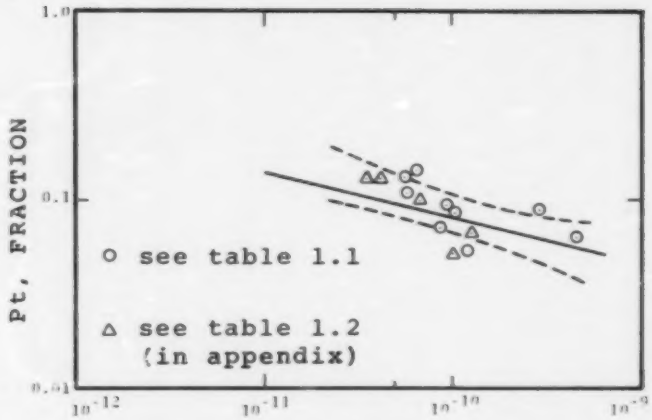


Figure 6-5. Experimental 1.0 μmA particle penetration for spray scrubber.

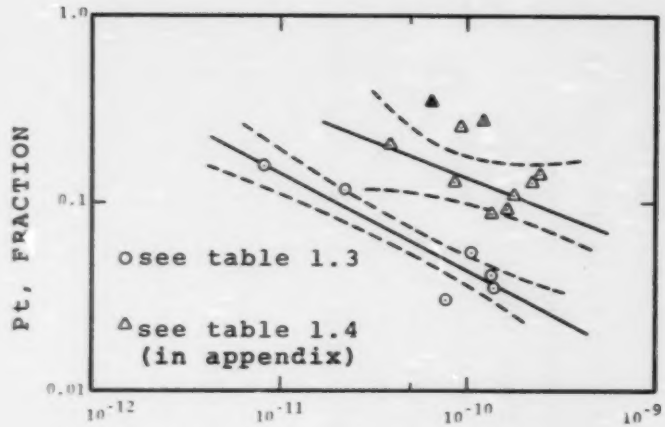


Figure 6-6. Experimental 1.0 μmA particle penetration for spray scrubber.

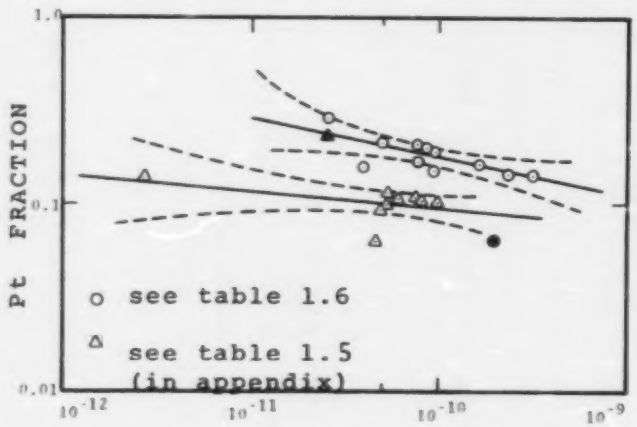


Figure 6-7. Experimental 1.0 μmA particle penetration for spray scrubber.

After the determination of the constants "A" and "B" for the straight line equation, the percent error for each data point was calculated. Those that indicated appreciable error (25% or greater) were eliminated (these points are shaded on the plots) and the least square straight lines were redetermined for the remaining number of data points. As shown in Table 6-1, four data points were thus not included in the determination of the least square straight lines out of a total of fifty-two points. This resulted in narrower bands for confidence limits and thus precluded the accounting of a typical scrubber performance.

The 90% confidence intervals for the mean values, "Pt", of the regression curve:

$$\ln Pt = A + B \ln q \qquad (6\text{-}6)$$

were established utilizing the t-distribution table, 90% confidence level, and n-2 degrees of freedom where "n" was the number of data points. The equations are presented in Table 6-1 and by straight lines on Figures 6-5 through 6-7. The 90% confidence intervals are also represented by broken lines on these figures.

In lieu of a rigorous mathematical model, the equations developed above can be used for predicting particle collection in FF/C spray scrubbers. For particles smaller than 2 μmA in diameter, the collection is mainly dependent on particle growth and flux forces. Thus the penetration was expressed as a function of "q" in the equations. The equations can be used to predict the amount of vapor condensation required in the scrubber for the designed penetration of fine particles. Application of the above equations is limited to the design of FF/C spray scrubbers with the configuration and operating parameters similar to the pilot

Table 6-1. FF/C SPRAY SCRUBBER DESIGN EQUATIONS

SCRUBBER OPERATING MODE	DESIGN EQUATION
One stage mode, cold water sprayed in all sections L/G ≃ 2.5 ℓ/m³ each stage	$Pt = 7.5 \times 10^{-5} q^{-0.31}$
Single stage mode, cold water sprayed in all sections, L/G ≈ 2.1 ℓ/m³ each stage, small liquid drops	$Pt = 2.7 \times 10^{-7} q^{-0.53}$
Single stage mode, cold water sprayed in all secitons, L/G ≈ 2.1 ℓ/m³ each stage, large liquid drops	$Pt = 3.4 \times 10^{-5} q^{-0.06}$
Three stages with co-current liquid/gas contact scheme, L/G ≈ 2.5 ℓ/m³ each stage	$Pt = 1.5 \times 10^{-2} q^{-0.08}$
Three stages with counter current liquid/ gas contact scheme, L/G ≈ 2.5 ℓ/m³ each stage	$Pt = 1.7 \times 10^{-3} q^{-0.2}$

scrubber evaluated in this study. It is noted however that the pilot scrubber was operated at near optimum conditions for maximizing particle collection and thus covers the practical design range for the horizontal FF/C spray scrubbers.

CHAPTER 7

ECONOMIC FEASIBILITY

Experimental results discussed in the previous sections, together with the theoretical and experimental studies reported by previous investigators, clearly show that fine particles can be collected with high efficiency in FF/C scrubbers. The economic feasibility of FF/C scrubbing is discussed in the following section. Since there has been no published study of an industrial FF/C scrubber, actual data on the economics of such a system are not available. Thus, the discussion is limited to preliminary predictions of costs based on the available information on FF/C scrubbing.

Some general economic features of FF/C scrubbing are discussed below. Experimental results plotted on Figure 5-7 indicate that it should require from 0.1 to about 0.25 g water vapor condensed/g dry gas in a FF/C scrubber to attain high collection efficiency for fine particles. Such a condensation ratio generally requires preconditioning of the scrubber inlet gas to increase its moisture content.

Gas preconditioning could be done either by direct introduction of spent steam if the gas is dry and has low enthalpy, or by the evaporation of sprayed water when enough enthalpy is available in the gas. Direct injection of steam is beneficial because it can increase the local saturation ratio above 1.0, which is necessary for the growth of hydrophobic particles.

Cooling water is needed to condense the desired amount of vapor in the scrubber. In an industrial system the water is cooled in an evaporative cooling tower using ambient air, and then recirculated to the FF/C scrubber. In cooling towers of conventional design, the cooling range is kept below about 17°C (30°F). A larger water temperature range can be achieved in cooling towers of special design but the costs will be higher

than usual, and there may be undesirable features such as fog formation. If the water temperature rise in the scrubber is 17°C (30°F), about 32 g of cooling water will be required to condense 1 g of water vapor.

COST COMPARISON

It is likely that one would have to make a choice between using high pressure drop or FF/C conditions in a scrubber system for fine particle collection. If equipment costs for the two types of system are roughly the same, most of the difference in operating costs will be due to power, water, and steam requirements. In order to compare the two approaches, operating costs have been estimated for an FF/C system and a high energy (venturi) scrubber and the results are described below.

As an example case we have taken flowrate of 1,700 Kg/min of dry gas (D.G.) with molecular weight of 29.0 and an initial humidity of 0.01 g H_2O/g D.G. Various inlet gas temperatures are considered and it is assumed that the gas will reach its adiabatic saturation temperature in the high energy (H.E.) scrubber and 49°C in the FF/C scrubber outlet. A 10°C lower outlet temperature than the assumed 49°C from an FF/C scrubber could generally be attained without great difficulty so that 49°C assumption is conservative. The saturated gas is assumed to travel from the scrubber to an induced draft fan and then to discharge. Thus the fan power requirement will depend on the humidity, temperature, and pressure of the scrubbed gas.

Costs were estimated for several operating modes of an FF/C scrubber and for some combinations of inlet gas temperature and pressure drop for an H.E. scrubber. Some illustrative results are shown in Figure 7-1, a plot of hourly operating costs against condensation ratio with parameters of scrubber type and operating conditions.

Assumptions and cost bases for Figure 7-1 are as follows:

1. Inlet dry gas flowrate is 1,700 Kg/min, pressure is 1.0 atm abs., humidity is 0.01 g H_2O/g D.G., molecular weight is

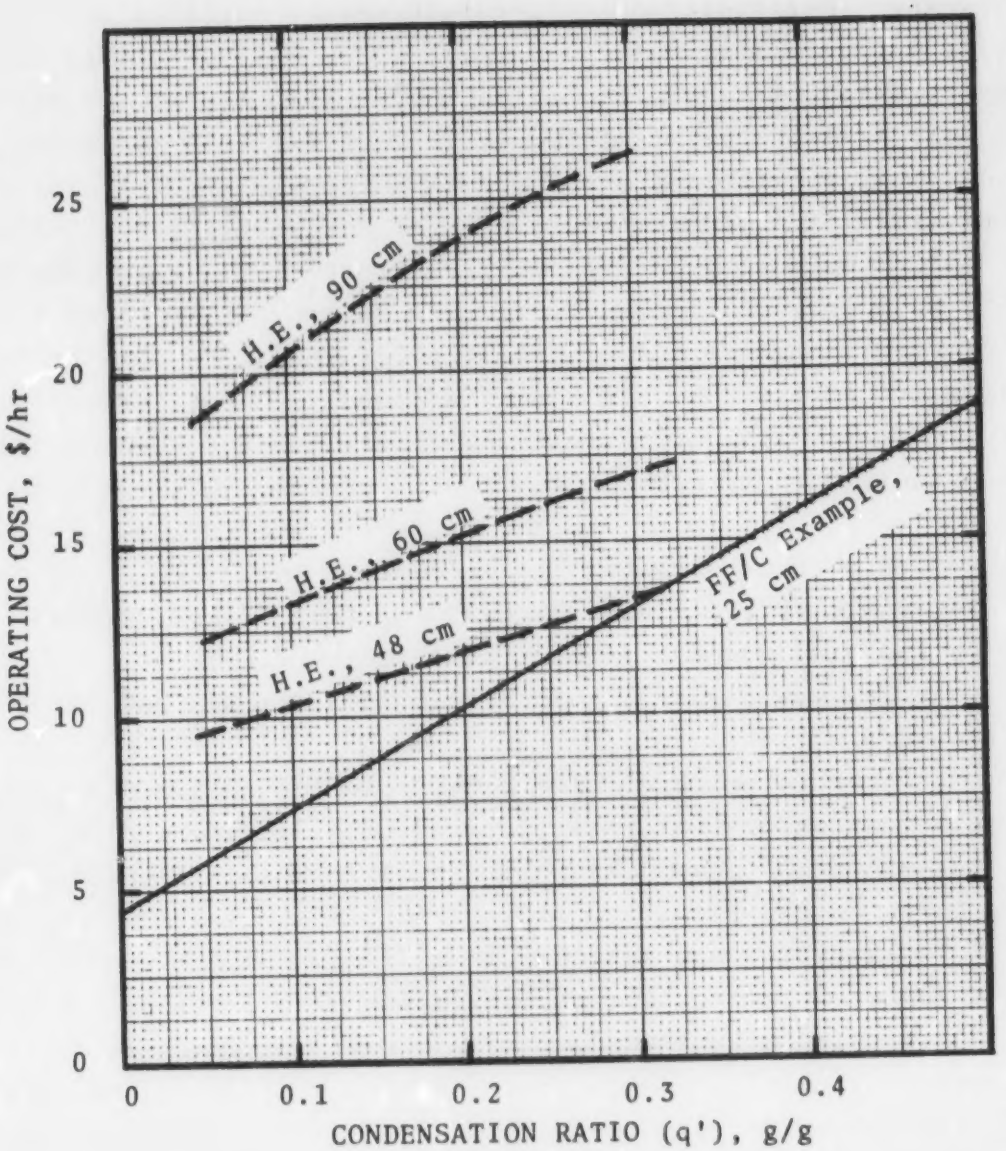


Figure 7-1. Operating cost comparison of FF/C and H.E. scrubbers.

29.0. Various inlet temperatures are considered.

2. Cooling water could cost from 0.26¢/MKg (1¢/Mgal) to 4.0¢/MKg. Recirculated cooling tower water might be available for about 0.9¢/MKg, based on quoted costs and on cooling tower depreciation plus pumping costs, and is used in this example.

3. A water cooling range of 17°C is taken to represent the combined effects of temperature range and water costs. Thus, while the temperature range for scrubber water entering at 40°C and leaving at 70°C after contacting gas saturated at 75°C would be 30°C (corresponding to 18 g water required per g of vapor condensed) the cost of cooling would be higher than for a 17°C range. By assuming that both water requirement cost are constant with "q'", it is implied that water cooling cost is proportional to cooling temperature range, which is conservative.

4. Electric power cost is 3¢/KWH and purchased steam cost is $6.40/MKg ($2.90/1,000 lb) based on fuel at $10.32/Kcal ($2.60/10^6BTU) and 85% generating efficiency.

5. Fan power cost is based on an overall fan and motor efficiency of 50%.

6. An FF/C scrubber can be designed for an overall power requirement equivalent to a 15 to 25 cm W.C. fan; whether spray, plate, or packed type. Fan power costs for the FF/C scrubber are based on the higher pressure drop; 25 cm W.C.

7. Particle penetrations for H.E. scrubbers are predicted as a function of pressure drop by means of the method developed by Calvert (1974). Although the pressure drop portion of the theoretical model predicts about 15% too high for given flowrates, the overall correlation appears to fit experimental penetration data for f≈0.5.

Results of Comparison

In addition to Figure 7-1, the results of this comparison are presented in Table 7-1, showing some combinations of gas conditions and operating costs. Table 7-2 contains plots of

Table 7-1. GAS CONDITIONS AND FAN POWER COSTS

Inlet Gas		Ad. Sat. Gas		Fan Power Cost for 1,700 Kg D.G./min, ($/hr)				
				Pressure Drop, cm W.C.				
Temp. (°C)	Humidity (g/gD.G.)	Temp. (°C)	Humidity (g/gD.G.)	15cm	25cm	48cm	60cm	90cm
260	0.01	49	0.08	$2.67	$4.47	$ 9.06	$11.50	$17.70
400	0.01	58	0.14	--	--	9.80	12.40	19.30
500	0.01	66	0.22	--	--	11.20	14.00	21.80
800	0.01	71	0.3	--	--	12.40	15.60	24.20
1000	0.01	75	0.39	--	--	13.50	17.00	26.00

Table 7-2. TYPICAL PENETRATIONS FOR PLATES AND SPRAY

	Penetration for 1 μmA dia. particles at q' shown				
Pilot Scrubber	0.05 g/g	0.1	0.15	0.2	0.25
5 Sieve Plates	0.22	0.17	0.12	0.078	0.06
Sprays	0.13	0.092	0.075	0.057	0.04

typical values of experimental penetration for 1 μmA diameter particle as a function of condensation ratio for plate and spray type FF/C scrubbers so that the cost data can be readily interpreted.

The three dashed lines are for the fan power costs associated with H.E. scrubbers operating at 48, 60, and 90 cm W.C. pressure drop (as indicated on the plot) and at actual volumetric flowrates corresponding to a given condensation ratio. To illustrate the meaning of these lines, gas at 600°C and humidity of 0.01 g/g would reach an adiabatic saturation temperature of 66°C and humidity of 0.22 g/g in a H.E. scrubber. The volumetric flowrate due to 1,700 Kg/min of dry gas and 374 Kg/min of water vapor would be about 2.2×10^3 m^3/min at 66°C and 1.0 atm absolute pressure. The volumetric flowrate will be higher at lower absolute pressure corresponding to negative inlet fan pressures equivalent to the pressure drop across the scrubber system.

The cost of fan power is computed from the actual volumetric flowrate and pressure drop by the use of the relevant assumptions and costs given above. In order to compare the cost for H.E. scrubbing to that for FF/C scrubbing, they have been plotted against the condensation ratio which could have resulted if gas at the inlet conditions had been treated in an FF/C system. For the 600°C inlet temperature the condensation ratio would be the difference between the adiabatic saturation humidity and the assumed FF/C outlet humidity; that is, q'=0.22-0.08 = 0.14 g/g.

At q'=0.14, Figure 7-1 shows the following:

Scrubber	Pt @ 1 μmA	Cost, $/hr
FF/C Spray	0.08	8.80
H.E. 48 cm W.C.	0.1	11.00
H.E. 60 cm	0.05	13.70
H.E. 90 cm	0.02	21.50
H.E. 42 cm*	0.125	9.50

Note: *Computed for comparison at same Pt as FF/C plate.

It can be seen from the above data that FF/C scrubbing would require lower operating costs than H.E. The cost advantage of FF/C scrubbing increases as the inlet gas enthalpy increases and the penetration requirement decreases. If low penetration is not required a low pressure drop H.E. scrubber may give satisfactory performance at lower cost than FF/C. The point where H.E. and FF/C scrubbing will have the same operating cost for the same efficiency, depending on FF/C scrubber type, is a gas temperature of about 400°C. The condensation ratio would be about 0.06 g/g and the predictions from Figure 7-1 and some additional computations for H.E. scrubbers are as follows:

Scrubber	Pt @1 mA	Cost, $/hr
FF/C Spray	0.12	6.30
H.E. 30 cm W.C.	0.21	6.30
H.E. 44 cm	0.12	9.00

In the "cold" operation mode (i.e. $q' \approx 0$), the spray gave the same or slightly better efficiency for a given power input than other types of H.E. scrubbers, such as gas atomized sprays. For example, at about 2.4 ℓ/m^3 in each of three sections, as in the pilot scale spray scrubber, the liquid pumping power would be equivalent to about 17 cm W.C. pressure drop in terms of fan power. The cut diameter of the spray scrubber is about 0.9 μmA. For a H.E. scrubber with a pressure drop of 17 cm W.C., the cut diameter if 0.92 μmA. Since the penetration at a given "q'" is lower for the spray than the H.E. scrubber, pre-formed sprays will be economically superior to H.E. scrubbers where there is any significant amount of condensation taking place.

Steam Introduction

While the performance of an FF/C scrubber at a given condensation ratio is better if part or all of the water vapor is introduced as steam (i.e. 100% H_2O), the cost of purchased steam will generally be prohibitively high. However, under the right circumstances the use of some steam introduction could be economical.

The steam required for injection could be low pressure <2 atm gage, (<30 psig) spent steam. It may be obtained from the feed line to the boiler condenser in a process plant or generated in a low pressure waste boiler in a metallurgical operation. In this case, the steam cost would be significantly lower and will depend on the specific manufacturing process. In general, if such steam is available for less than $1.88/MKg, the operating costs for a FF/C scrubber would be lower than for a venturi scrubber.

Figure 5-7 indicates that the "q" requirement levels out around q'=0.15, so that proportionately less condensation is required to obtain penetrations lower than 5% in a FF/C scrubber. Thus, in this region, a FF/C scrubber using some purchased steam would have lower operating costs compared to a venturi scrubber. Also, as the most important factors in FF/C scrubbing, diffusiophoresis and particle growth by condensation are practically insensitive to particle size, FF/C scrubbing would become economically more attractive as the size of the particles to be controlled gets smaller, in the range of 0.01 μm to 10 μm diameter.

Industrial Application Costs

Calvert et al. (1973) have evaluated the economic feasibility of FF/C scrubbing systems designed for two industrial sources: A Basic Oxygen Furnace and a Kraft Recovery Furnace. The gas cleaning devices in these systems were a FF/C spray scrubber for the Basic Oxygen Furnace and a combination of a venturi evaporator-scrubber followed by a FF/C condenser vessel with a spray scrubber for the Kraft Recovery Furnace.

The economic feasibility of FF/C scrubbing for a gray iron cupola is evaluted below. Due to the different designs and operating practices for cupolas, it is not possible to generalize emission characteristics so a specific cupola was selected for the case study. Emissions from this cupola are now controlled with a high energy scrubber whose performance was measured by A.P.T. (Calvert et al. 1974). Information on emissions, system behavior and costs were obtained from the cupola

operators. The FF/C scrubber system was designed for the same level of particle control as the existing system and the equipment and operating costs are compared.

CUPOLA EMISSION CONTROL

Gray iron foundries use cupola, electric-arc, electric-induction and reverberatory air furnaces to obtain molten metal for production of castings. The iron melting process is the principal source of emissions in the foundry industry. Cupola furnaces are most commonly used for the melting operations. In the foundry industry, cupola emissions are dominant, totaling over 105,000 ton/yr as reported by M.R.I. (1971).

The cupola emissions are presently controlled by high energy scrubbers, fabric filters (baghouses) and electrostatic precipitators. FF/C scrubbers are uniquely suited for cupola emission control, due to the combination of high stack gas temperatures (over 900°C), fine particle sizes (d_{pg}~1.5 μmA), moderately high dust loadings (over 3 g/DNm^3) and the presence of contaminant gases.

The FF/C system described below was designed for a 2 m (80") diameter cupola. Presently the cupola emissions are controlled with a high energy scrubber system. Details on the performance of this system together with the cost data have been reported by Calvert et al. (1974). The cupola operation is breifly described below:

Size: 2 m (80") I.D., 9.8 m (32') high from tuyeres to afterburners and 7.6 cm (25') additional height to the top. The shell is water cooled to a height of 6 m (20') and then refractory lined to the top. The fuel gas flow to the two afterburners is controlled to maintain the off-take gas temperature between 870°C and 930°C.

Charge: Each charge consists of about 2,700 Kg of metal (mostly case iron), between 270Kg to 320Kg of coke and fluxes as required. On an average there are 12 charges per hour.

The cupola emissions were reported to be as follows:

Flue gas rate = 3,400 Am^3/min (119,500 ACFM) @ 900°C.

Flue gas humidity = 0.01 $\frac{g\ vapor}{g\ dry\ gas}$, from humidity of the ambient air.

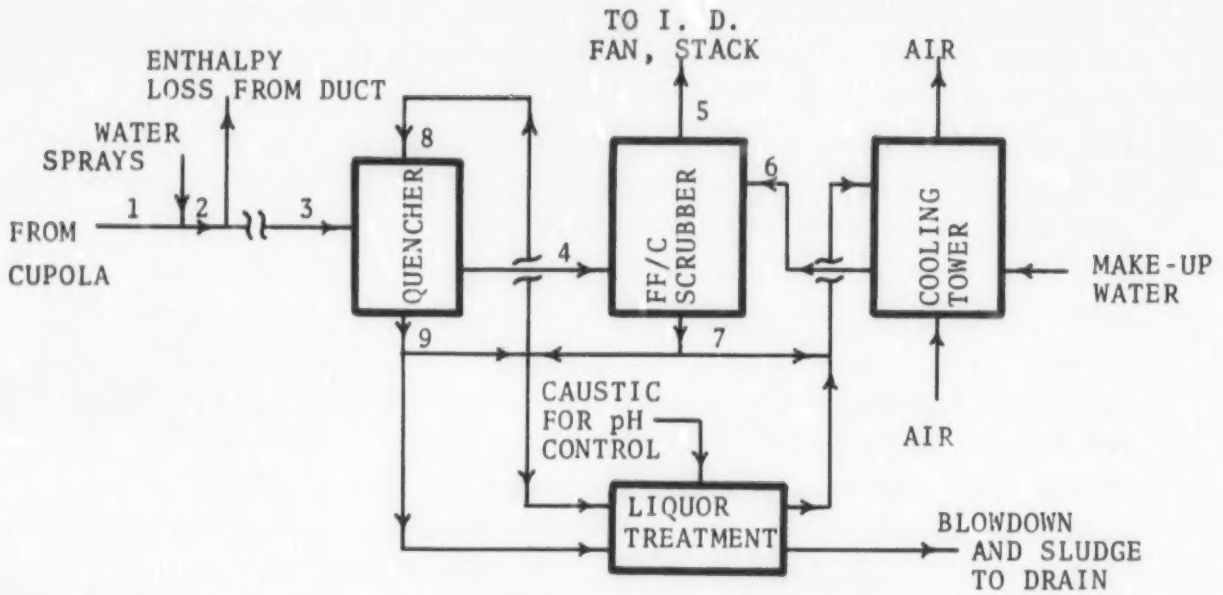
Particulate characteristics: 3.5 g/DNm^3 (8 gr/DSCF), log normally distributed with mass mean diameter, d_{pg}=1.15 μmA and σ_g=1.7.

The present high energy scrubber system has an overall particulate removal efficiency of 97% at the scrubber pressure drop of 275 cm W.C. (Calvert et al, 1974).

The FF/C Scrubber System

The FF/C scrubber system was designed to yield 97% particulate collection efficiency, identical to the performance of the high energy scrubber. A spray configuration was selected for the FF/C scrubber due to the low pressure drop requirement. Based on the FF/C spray scrubber tested in this study, q'=0.18 is considered sufficient to achieve the desired particulate removal, with the overall liquid sprayed to gas flowrate ratio of 4.5 ℓ/m^3(34 gal/MCF).

A process diagram of the FF/C scrubber system is shown in Figure 7-2. As described earlier, stack gas from cupola offtake is maintained at about 900°C by adjusting the afterburners. Immediately downstream of the refractory-lined offtake, 150 ℓpm of water is sprayed in as fine mist, cooling the gas to 427°C. This serves the purpose of reducing heat losses from the 90 m long duct to the scrubber system, as well as permitting the use of smaller diameter mild steel duct. Gas temperature at the quencher inlet is determined to be 280°C after accounting for the heat losses.



	STREAM NO.	TEMP °C	VOLUME FLOWRATE Am^3/min or ℓ/min	GAS HUMIDITY g vapor / g D.G.	PRESS cm W.C.	LOADING g/INm^3
GAS	1	900	3,400	0.01	-2	3.5
	2	427	2,480	0.16	-7	3.5
	3	280	1,850	0.16	-15	3.5
	4	69	1,300	0.26	-20	3.5
	5	49	970	0.08	-35	0.105
LIQUID	6	27	5,870			
	7	46	6,040			
	8	64	400			
	9	69	300			

FIGURE 7-2 - Process diagram for cupola gas cleaning

The gas is then further cooled and humidified by recirculating water sprays in the quencher. As the size distribution of particles in the stack gas is fine, with over 99% by mass of particles smaller than 5 μmA, water sprays in the quencher are not expected to remove any significant amount of particles. The desired particulate removal is achieved in the FF/C spray scrubber. The scrubbed gas is cooled down to 49°C in the scrubber, condensing out 0.18 g vapor/g d gas on the liquor sprays. The overall pressure drop across the system is determined to be 35 cm W.C.

The liquor system includes a cooling tower and provisions for clarification and pH control of the recirculated liquid. The uniformly packed cooling tower uses ambient air for evaporative cooling of the liquid sprayed in the scrubber. Clarification of the recirculated liquid is attained by settling out the suspended solids in tanks, with a total retention time of about 45 minutes. The settling process is enhanced by the addition of coagulants. Caustic soda solution is added in the tanks to maintain the pH between 6 and 7. A constant blowdown from the tanks controls the concentration of dissolved solids in the liquid stream. A water wash is provided in the cooling tower to periodically clean out scale formed on the packing surface. City water is added into the cooling tower to make up for the blowdown, entrainment, evaporative and other losses from the recirculated liquid system.

Cost Comparison

Equipment for the system shown schematically in Figure 7-2 was selected and sized for the purpose of cost estimation. Capital cost information was obtained from the following sources: A.P.T. Scrubber Handbook (1972), Cost Engineering in the Process Industries (1960), Modern Cost Engineering Techniques (1970), and Chemical Engineers' Handbook, Fifth ed., (1973). The method was based on

calculating the F.O.B. equipment cost and then multiplying by various factors for the costs of internals, piping, instrumentation, etc. The capital costs were then adjusted to a common time base, 1974, using the Marshall & Stevens Equipment Cost Index.

Installation costs for the scrubber system, to include modifications in existing process, site preparation, foundation, start-up, etc. were not determined, as they are expected to be comparable to the costs for the high energy scrubber system. Similarly, the operating costs for labor, liquid treatment, and solid disposal, together with the maintenance costs for labor and materials, are expected to be comparable for the two scrubber systems. Thus, the only operating costs compared are the electrical power requirements and annualized capital charged and depreciation taken as 20% of the capital costs. Table 7-3 shows the cost comparisons.

The FF/C scrubber system requires additional equipment such as the quencher and the cooling tower. Due to the higher flow requirements of recirculated liquid, the liquid system costs are also higher for the FF/C system compared to the high energy (H.E.) scrubber. However, these costs are more than offset by the higher cost for fans for the H.E. scrubber system. Three fans are required for the H.E. system, adding up to 1,080 KW (1,450 HP) as compared to one 127 KW (170 HP) fan required for the FF/C system. Note that costs for piping and ducting for both the systems are expected to be the same, although they are significantly different. The FF/C system has a higher piping requirement and requires the 90 m duct to be lightly insulated. These costs are expected to approximately offset the cost of additional ducting used in the H.E. system to jacket the 90 m duct.

Table 7-3. COST COMPARISON OF CUPOLA EMISSION CONTROL SYSTEMS

COST ITEMS	High Energy Scrubber System ($)(1)	FF/C Scrubber System ($)
A. Capital Costs		
1. F.O.B. quencher with internals, flange to flange	-- (4)	12,140
2. F.O.B. scrubber with internals, flange to flange including entrainment separator	18,600	32,460
3. F.O.B. cooling tower	--	34,950
4. Fans, motors and motor starter	156,370	35,000
5. Liquid treatment and solid handling equipment, including pumps.	50,030	80,000
6. Piping and ducting (2)	102,570	102,570
7. Instrumentation and electrical material (3)	22,900	15,640
TOTAL EQUIPMENT COST	350,470	312,760
B. Annual Operating Costs		
1. Electrical power for fans and pumps.	102,560	38,900
2. Annualized capital charges and depreciation (20% of capital costs)	70,100	62,550
TOTAL	$172,660	$101,450

Notes:

1. Actual costs obtained from the user, converted to 1974.
2. Due to equivalent complexity, the costs were assumed same for both systems.
3. Taken as 5% of equipment costs for the FF/C system.
4. Quench spray costs for both the systems are included in the ducting costs.

A comparison of costs for the two systems indicates that the total equipment costs are approximately the same. The H.E. system, however, costs about $63,500 more per year to operate, as the annual cost for electrical power is more than 2.6 times that for the FF/C system. Electrical power cost of $0.03/KW-HR was used for the above calculations. Power costs have increased steadily in recent years and there are no immediate indications for a change in this trend. As the cost of electrical power increases and energy conservation becomes more important, the FF/C scrubbing system will prove to be more attractive, compared to a high energy scrubbing system.

CHAPTER 8

FUTURE RESEARCH RECOMMENDATIONS

The preliminary objective of examining the technical and economical feasibilities of FF/C scrubbing for the collection of fine particles, through experimental evaluation, has been achieved in this study. It has been clearly shown that FF/C scrubbing is capable of high efficiency fine particulate removal. Areas of economic application of FF/C scrubbing at industrial sources have been identified. These include some of the major stationary air pollution sources in the U.S.A. as listed in the Midwest Research Institute report (1971). Mathematical design models have been developed also for the spray scrubber studied. To continue this development work so that the advantages of FF/C scrubbing could be derived for industrial application, we recommend future research work in the following areas:

1. Demonstration of the feasibility of FF/C scrubbing on selected industrial sources.
2. Theoretical and experimental evaluation of other low energy scrubber configurations to determine the best configuration applicable to FF/C scrubbing systems.
3. Development of evaporative cooling devices suited for the cooling of scrubber liquid containing suspended and dissolved solids.
4. Theoretical and experimental determination of the specific details of heat and mass transfer in gas-liquid systems, the nucleation of condensation and other matters which critically affect the applicability of FF/C scrubber design equations.

DEMONSTRATION OF FF/C SCRUBBING

A detailed test program to demonstrate FF/C scrubbers at pilot scale for the control of fine particulate emissions from three industrial sources is described below. The following criteria were used for selecting the industrial sources:

I. The national importance of the industrial particulate emission sources as major pollutants.
II. Applicability of FF/C scrubbing in terms of its technical and economic feasibility.
III. Sources which are either difficult or expensive to control with presently available particulate control devices.

Three sources were selected which would enable demonstration of the operational reliability of all the components of an FF/C scrubbing system. These sources are described below:

Secondary Nonferrous Metals Recovery Furnace

The secondary nonferrous smelting and refining industry generally uses gas-fired furnaces to recover copper, aluminum, lead and zinc from scrap and dross. The nature of furnace operations is such that emissions vary widely during the cycle from charging the scrap to pouring a melt. Peak emission surges occur in nearly all the furnace operations. The principal emissions from these furnaces are particulates in the form of smoke, dust, and metallic fumes. However, during copper wire reclamation, considerable amounts of acidic and corrosive gases comprised of fluorine and chlorine compounds are also present, depending on the composition of the wire insulation. With emission rates of about 127,000 ton/year, this industry was ranked among the top fifteen national source pollutants in a survey by Midwest Research Institute (1971).

Due to the cyclic nature of the emission, high flue gas temperatures (∿500°C to 900°C), presence of corrosive gases and high efficiencies required for fine particulates, the recovery furnace emissions have been difficult and expensive to control. Generally, afterburners are used following the furnace to burn out hydrocarbons in the flue gas. High energy scrubbers, electrostatic precipitators and fabric filters have then been applied to remove the particulates. None of these have proven reliable for maintenance free operation. No control device is presently available to control emissions from copper wire recovering operations, although over 300,000 ton of insulated wire is recycled annually resulting in emissions exceeding 41,000 ton/year.

We recommend that FF/C scrubbing should be demonstrated on a recovery furnace, especially one operated for copper wire reclamation. A pilot scale system with a capacity of 140 to 280m^3/min is recommended. A small furnace with a process load of about 450 Kg/hr, with 20-minute cycles, would be ideally suited for the demonstration. The total flue gas emission of such a furnace would be in the range of the pilot scale FF/C scrubber capacity so that the effect of the cyclic nature of emission could be best evaluated. This would permit also a study of the FF/C system performance for the simultaneous removal of fine particulates and corrosive gases, using alkaline scrubber liquor.

Glass Furnace

The glass manufacturing industry, and especially the container glass industry, is faced with a nation-wide need for the application of particulate control systems on the glass furnaces. Glass furnace emissions have been difficult and expensive to control due to a high fraction of fine particulates,

high stack gas temperatures and the presence of gaseous contaminants. However, these emission properties are favorably suited for economic application of FF/C scrubbing.

A typical furnace produces from 80 to 140 metric tons of glass per day on a 24 hrs/day schedule. Typical flue gas properties for a furnace producing amber glass are as follows:

Gas Conditions:
- Flowrate: 300 m^3/min @ 20°C
- Temperature: 450°C

Particulates:
- Loading: 0.2 g/m^3 @ 20°C
- Emissions: 4 Kg/hr.
- Composition: ~90% Na_2SO_4
  ~10% $CaSO_4$
  trace amounts of other constituents

The particles are ~1.0 μmA, with geometric standard deviation less than 3.

Gaseous contaminants:
- SO_x: 80 ppm
- NO_x: 1,500 ppm

In addition to the removal of gaseous contaminants, over 80% removal of particulates is required and the opacity limited to less than 20%. An FF/C scrubber has the additional advantage of particle growth, as ~90% particulates are soluble in water and would grow at a saturation ratio of less than one. This would be one of the major aspects of the demonstration. Again, a pilot scale system with a capacity of 140 to 280m^3/min is recommended.

Gray Iron Foundry Cupola

Gray iron foundries use several types of furnaces to melt and recover iron from scrap for the production of castings. Cupola furnaces are most prominently used for the melting operations. The iron foundry industry was ranked among the top 15 national stationary-source pollutants in the Midwest Research Institute (1971) survey. In the foundry industry, cupola particulate emissions are dominant, totaling over 105,000 ton/year. Physical processes, chemical reactions, and the quality of scrap affect the emissions of dust and fumes from cupola, thus no typical flue gas condition can be defined. For example, emissions from a 86 cm (34") cold blast cupola with a production rate of 45 Kg (100 lb) molten iron per minute are listed below:

Flue gas rate = 520 A m^3/min (18,350 ACFM) @ 980°C
Flue gas rate = 115 N m^3/min (4,000 SCFM)
NOTE: The flue gas rate and temperature are maintained constant by adjusting gas flowrate to an afterburner located above the charge door.
Average flue gas composition, before afterburn, vol %:
CO_2: 12%
CO : 14.9%
N_2 : 73.1%
Particulate loading: 1.0 g/DNm^3 (2.3 gr/DSCF)

The particulate size distribution data reported in the literature for cupola emissions were found to vary considerably from source to source. Due to the carbon particles present in the emission, the particles are considered to be non-wettable.

Cupola emissions have been difficult and expensive to control due to the high emission rates of fine particulates, high gas temperatures and significant changes in the emission characteristics during the operation cycle. At present,

electrostatic precipitators, high energy scrubbers and fabric filters (bag houses) are used to control these emissions. The high gas temperatures and fine particulate loadings prompt the economic use of FF/C scrubbers. Again, a 140 to 280m^3/min pilot scale FF/C system is recommended.

A detailed demonstration test program, including the cost and time estimates, is described below. Although the details of FF/C scrubbing system design will be different for each source, the overall process design, illustrated in Figure 8-1, will be the same. Since the test matrices for the demonstrations would also be of comparable complexities, we expect that the cost and period of performance for each demonstration will be the same. Any variations in these estimates can be easily accommodated when more details on the installation and operation of the industrial source in question are available.

In outline, the objectives consist of the following tasks:

1. Select a company which operates a suitable plant involving one of the above operations for the demonstration of FF/C scrubbing and obtain required clearances from the local air pollution control agency.
2. Design the demonstration scrubber system on the basis of:
   A. Pertinent data concerning the source obtained through source testing.
   B. Evaluations of alternative FF/C scrubber system designs.
3. Prepare a detailed test plan describing:
   A. The measurement techniques to be used.
   B. Error analysis of the measurement techniques.
   C. The proposed test matrix.
   D. The data handling procedures.

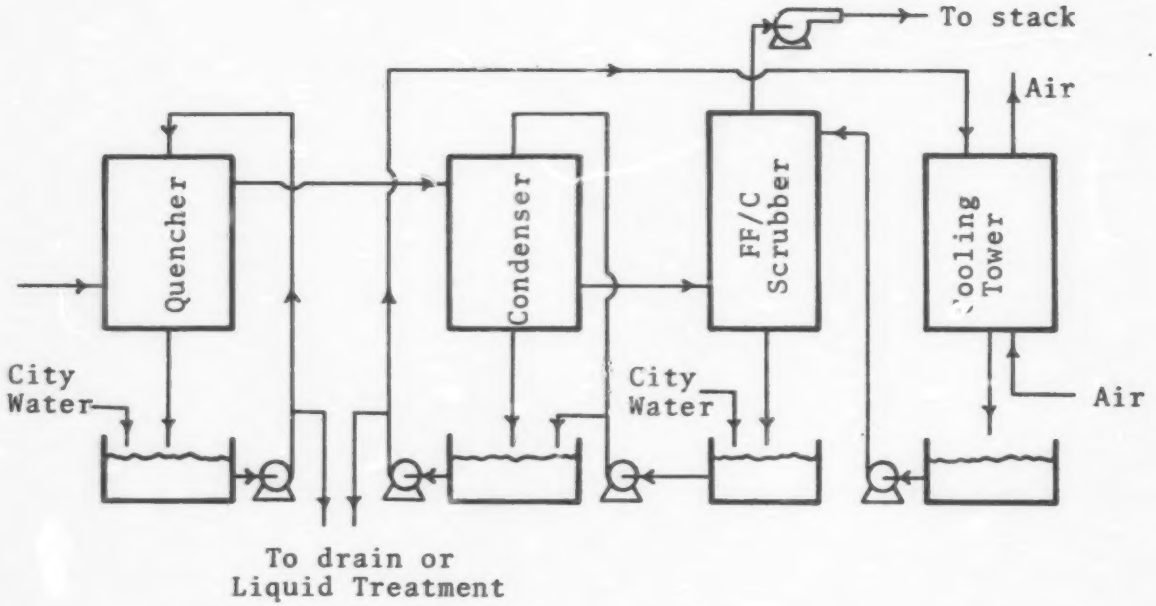


Figure 8-1 - Typical process design of a FF/C scrubber system

4. Fabricate, install and start up the FF/C scrubber system as developed in 2 above.
5. Conduct the test program as developed in 3 above.
6. Remove the pilot FF/C scrubbing system and restore the site to its normal condition less fair wear and tear.
7. Conduct an engineering and cost analysis of the FF/C scrubber system to evaluate:
   A. Scrubber operating and capital cost.
   B. Scrubber operation and maintenance problems.
   C. Scrubber reliability.
   D. Scrubber performance.
8. Based on the above analysis and the additional information available on scrubber design, design and estimate the cost of an optimum FF/C scrubber system for the industrial source.
9. Define the areas of FF/C scrubbing in which additional information is needed to improve the viability of the FF/C scrubber application.
10. Survey emission conditions for similar sources to determine a group of industrial operations where the optimum FF/C scrubbing system developed above is economically applicable with minor modifications.
11. Recommend a test program to demonstrate a full-scale FF/C scrubbing system on a simliar industrial source.

For the purpose of estimating the cost and time requirements, the following task breakdown was used:

Task 1 - Select company

a. Survey the industry and contact companies
b. Preliminary screening
c. Contact screened candidates to obtain additional information and perform sampling, where needed.

d. Refine calculations of conceptual designs based on "c" above.
e. Consult the contracting agency.
f. Select the company for the demonstration.
g. Consult the local air pollution control agency.
h. Finalize the arrangements.

Task 2 - Design the demonstration pilot plant

a. Obtain more data on the source
    1. Sample the source
    2. Conduct small-scale (10-20 CFM) tests on the source to test out concepts for scrubbing, liquor cooling, monitoring, etc.
b. Evcluate alternatives by means of:
    1. Preliminary designs
    2. Laboratory bench scale tests
    3. Laboratory pilot scale tests
    4. Additional small-scale tests at source
    5. Finalize alternative designs
    6. Compare alternative designs
    7. Consult contracting agency
    8. Consult company
    9. Clear with local air pollution control agency
    10. Make detailed design and specifications of demonstration pilot plant.

Task 3 - Prepare detailed test plan

a. Develop plan
b. Error analysis
c. Define procedures
d. Finalize measurement and monitoring procedures

Task 4 - Fabricate, install, start up

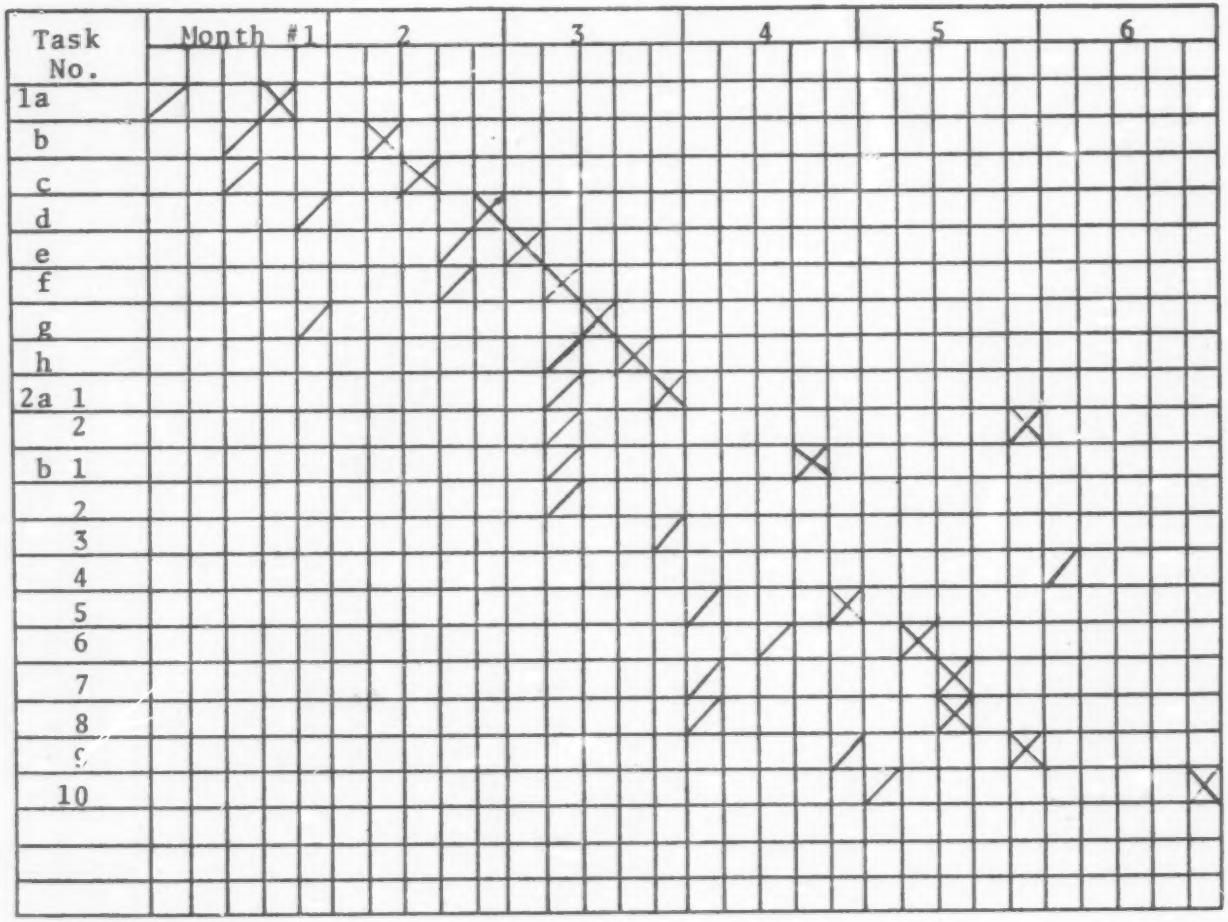
a. Select vendors and place orders
b. Arrange for site modifications
c. Follow up vendors and assemble components
d. Install pilot plant
e. Start up pilot plant

Task 5 - Conduct test
  a. At near-optimum conditions
  b. At excursions from optimum
  c. Configuration variations
Task 6 - Remove pilot system and restore site
Task 7 - Engineering analysis
  a. Operating and capital costs
  b. Operating and maintenance problems
  c. Reliability
  d. Performance
    1. Scrubber
    2. Liquor system and other auxiliaries
Task 8 - Optimum FF/C system
  a. For this plant condition
  b. For other capacities.
Task 9 - Evaluate FF/C scrubbing system performance to define areas for additional investigation
Task 10- Survey emissions from other sources to determine a group of operations with similar emission problems
Task 11- Recommend full scale test program

A performance schedule for this program is described in Table 8-1. The overall period of performance is 18 months for the demonstration program. It is noted that additional demonstration programs performed on the other industrial sources would require 14 months, if performed by the same contractor.

A detailed cost breakdown for the demonstration program is described in Table 8-2. It is noted that the costs were based on 1974 prices and for the FF/C scrubbing system only. If there are special construction and installation problems at the industrial source, the costs should be adjusted accordingly. It is expected that additional demonstration

TABLE 8-1: ESTIMATED SCHEDULE OF PERFORMANCE



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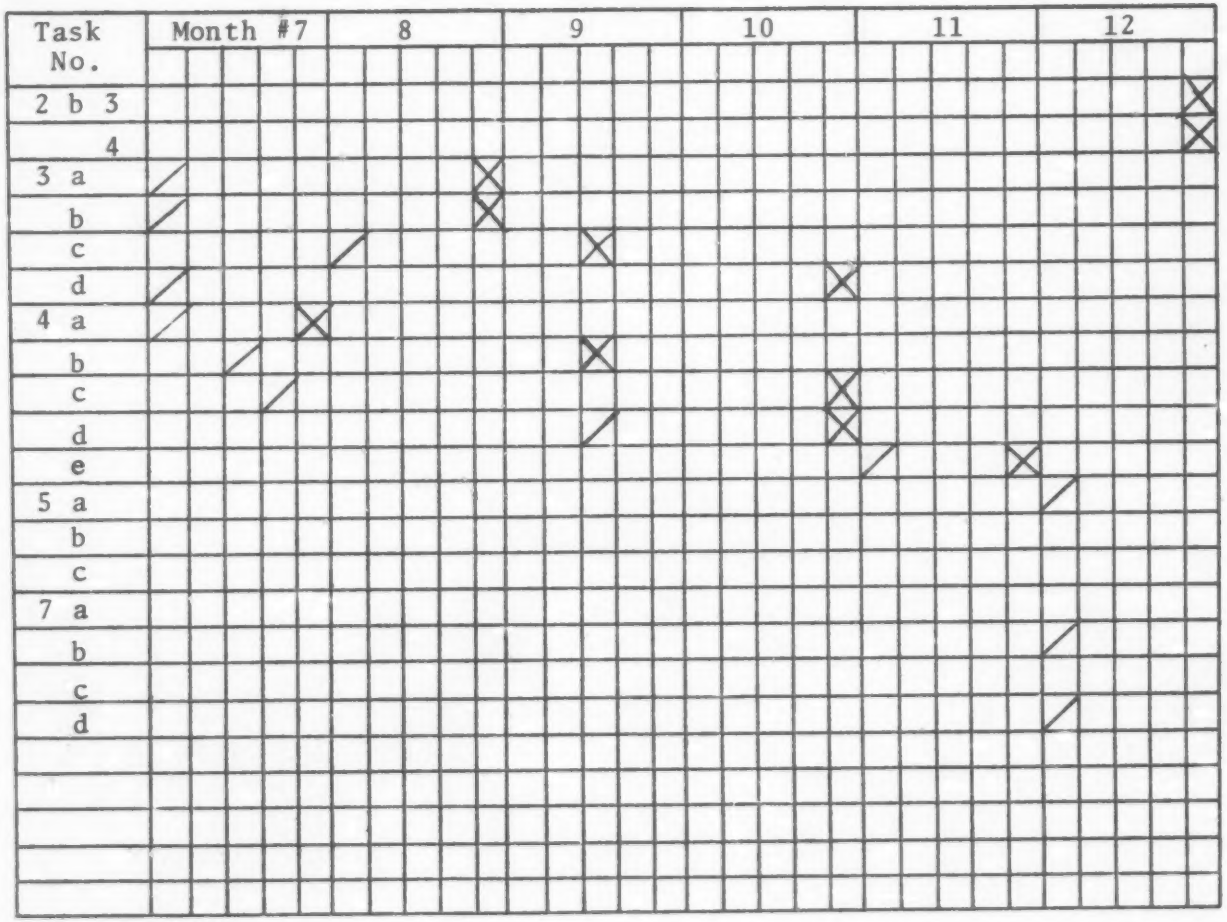

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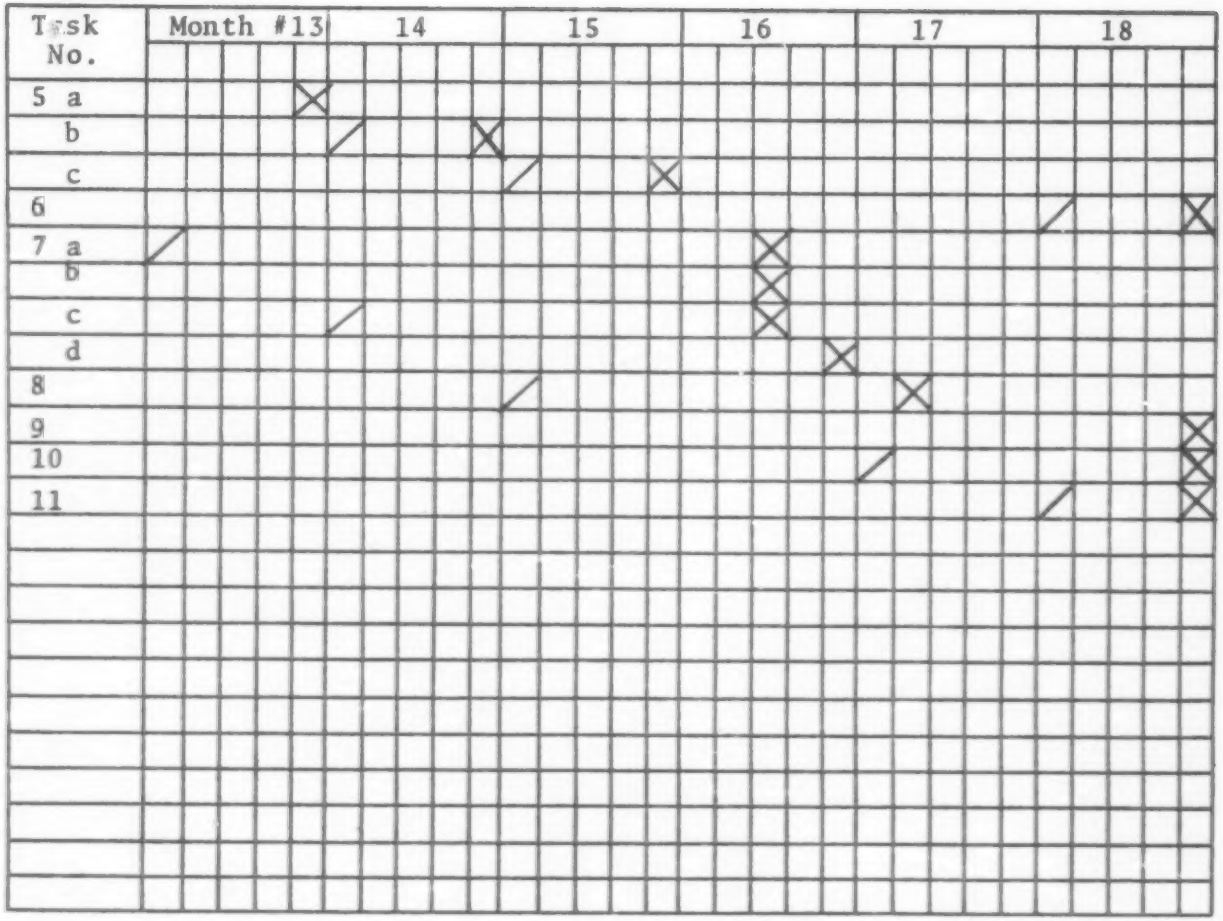

programs at the other industrial sources would cost about 80% overall, if performed by the same organization.

Table 8-2. DETAILED COST BREAKDOWN

Task No.	Direct Labor ($)	Other Direct Costs ($)
1	16,000	4,000
2	32,000	18,500
3	15,000	5,000
4	19,000	40,000
5	19,500	4,500
6	6,500	---
7	4,500	2,500
8	4,500	---
9	4,000	---
10	5,000	---
11	4,000	---
TOTAL	130,000	74,500

The above estimates were made on the assumption that the performing organization is eminently qualified in the research and development field, with special knowledge, background and interest in the specific field of particulate removal by FF/C scrubbing.

EVALUATION OF OTHER SCRUBBER CONFIGURATIONS

During the performance of this contract, the horizontal spray scrubber was evaluated, when operated in the FF/C scrubbing mode. Several other configurations of conventional and novel designs are presently available for low pressure drop scrubbing, such as the mobile bed scrubber and the packed bed scrubber with conventional and new packings. We recommend that these configurations be evaluated to determine their applicability to FF/C scrubbing. The following approach is recommended:

1. Survey scrubber manufacturers and users to assimilate design and operating information on low energy scrubbers with high gas residence times. The scrubbers should be multi-stage or continuous contact type.
2. Screen and select promising scrubber configurations based on theoretical evaluation of the scrubber performance when operated in the FF/C scrubbing mode, for the collection of fine particles.
3. Conduct a limited bench scale study to obtain information in the critical areas of scrubber operation, so that the FF/C scrubber model could be theoretically derived.
4. Determine the technical and economic feasibilities and the special area of application for these scrubbers by using the models developed above. The feasibilities should be determined by a comparative evaluation of all the FF/C scrubbers considered.
5. Select promising scrubber mechanisms and conduct a detailed experimental study as follows:
   a. Laboratory pilot scale study with scrubber capacity between 14 and 28 m^3/min.

b. Pilot scale demonstration on selected industrial sources with scrubber capacity between 140 to 280 m^3/min.

c. Full scale demonstration on a selected industrial source.

It is noted that performance of each of the above tasks would depend on the results of the preceding tasks. The program objective is to determine FF/C scrubber configurations best suited for specific industrial operations or a group of operations with common particulate control problems.

DEVELOPMENT OF LIQUOR COOLING SYSTEM

Due to the large requirement of cold scrubber liquor and the complications introduced by dissolved and suspended solids, the liquor cooling procedure has a significant effect on the economics of a FF/C scrubber system. The scope of the proposed work is to evaluate the liquor cooling system alternatives, select the most promising system and make an experimental study to determine its performance, economics and applicability.

The following approach is recommended:

1. Determine all factors affecting the liquor cooling system for a FF/C scrubber. These include such things as economic considerations, effect on scrubber performance and the concentrations of dissolved and suspended impurities in the liquor.
2. Evaluate cooling system alternatives and select the most promising for experimental study.
3. Conduct an experimental study on a suitable scale to determine its performance, economics, applicability and scale-up considerations.

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Table 1.1 HORIZONTAL SPRAY SCRUBBER; OPERATING CONDITIONS AND PERFORMANCE

Dust used: Titanium dioxide, -16 mesh
Spray configuration: Cold water sprayed in all of the three sections and drained out through a common outlet. Thus, scrubber operated in the single stage mode.
Inlet water flowrates: First Section: 1.05 liters/sec @ 2.67 kg/cm²
Second Section: 1.09 liters/sec @ 2.67 kg/cm²
Third Section: 1.0 liters/sec @ 2.85 kg/cm²

Run No.	Gas Inlet Conditions				Liquid Temp. (°C)		Scrubber Pressure Differences (cm W.C.)		
	Flow ($\frac{DNm^3}{min}$)	Temp (°C)	Moisture (% vol.)	Relative Humidity (%)	In	Out	ΔP_S	ΔP_E	ΔP_O
1	26.2	14.8	0.6	29	11	9	+0.9	-0.7	+0.2
2	25.9	12.8	0.6	35	11	9	+0.9	-0.6	+0.2
3	25.3	44.5	9.5	92	18	20	+0.9	-1.1	-0.2
4	24.6	45.5	10.0	97	19	24	+0.9	-1.0	-0.1
5	24.8	44.5	9.9	100	19	24	+0.9	-1.0	-0.1
6	20.8	46.3	9.9	92	17	21	+0.9	-1.1	-0.2
7	22.0	49.3	9.6	78	16	21	+0.8	-0.7	+0.1

Run No.	Particulate							q' x10	$\overline{Pt}$ %
	Load x 10^3 (g/DNm^3)		d_{pg}		σ_g		n_i x10^{-6}		
	In	Out	In	Out	In	Out			
1	192.0	84.0	1.00	1.00	2.0	1.8	6.8	---	43.8
2	180.0	84.0	1.13	1.10	1.9	1.6	4.4	---	46.7
3	106.2	8.3	1.09	0.96	2.0	1.4	3.2	0.5	7.8
4	91.1	11.9	0.99	0.95	1.7	1.6	1.0	0.5	13.1
5	107.6	11.1		Filter run				0.5	10.3
6	138.1	13.3		Filter run				0.5	9.6
7	53.3	3.5		Filter run				0.5	6.6

Note: ΔP_S : pressure difference across the scrubber

ΔP_E : pressure difference across the entrainment separator

ΔP_O : overall pressure difference, $\Delta P_S - \Delta P_E$, positive sign denotes pressure gain while pressure loss is denoted by a negative sign.

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Table 1.1 (continued)

Run No.	Gas Inlet Conditions				Liquid Temp. (°C)		Scrubber Pressure Differences (cm W.C.)		
	Flow ($\frac{DNm^3}{min}$)	Temp (°C)	Moisture (% vol.)	Relative Humidity (%)	In	Out	ΔP_S	ΔP_E	ΔP_O
8	22.9	57.3	15.6	86	20	25	+0.9	-0.9	---
9	22.8	57.0	15.7	86	21	27	+0.8	-0.9	-0.1
10	23.7	58.0	16.6	86	21	26	+1.0	-1.1	-0.1
11	23.0	57.5	16.8	90	20.5	25.5	+0.9	-0.9	---
12	22.3	64.5	23.3	90	22	40	+1.0	-1.0	---
13	21.9	66.5	25.7	90	22	43	+1.0	-1.0	---
14	22.3	67.0	25.5	89	23	45	+1.0	-1.0	---
15	23.3	67.8	25.5	85	23.5	44.5	+1.1	-1.0	+0.1

Run No.	Particulate								
	Load x 10^3 (g/DNm^3)		d_{pg}		σ_g		n_i x10^{-6}	q' x10	$\frac{\Delta P_t}{q'}$
	In	Out	In	Out	In	Out			
8	72.8	5.4	1.13	0.96	1.7	1.6	2.0	0.9	7.5
9	110.6	5.1		Filter run				0.9	4.6
10	113.4	5.2	1.31	0.92	1.9	1.6	1.5	1.0	4.5
11	97.3	3.7		Filter run				1.0	3.8
12	58.7	2.3		Filter run				1.5	3.9
13	46.6	2.6	1.36	1.00	2.0	1.6	0.7	1.6	5.6
14	136.0	7.6	1.29	0.90	1.9	1.6	1.9	1.6	5.6
15	154.7	7.5		Filter run				1.7	4.8

Table 1.1 (continued)

Run No.	Gas Inlet Conditions				Liquid Temp. (°C)		Scrubber Pressure Differences (cm W.C.)		
	Flow ($\frac{DNm^3}{min}$)	Temp (°C)	Moisture (% vol.)	Relative Humidity (%)	In	Out	ΔP_S	ΔP_E	ΔP_O
16	21.1	68.5	27.7	90	22	46	+0.9	-0.9	---
17	17.2	73.5	34.1	91	25	50	+0.8	-0.7	+0.1
18	17.7	73.0	35.0	95	27	55	+1.0	-0.7	+0.3
19	17.7	74.0	34.0	89	27	52	+0.9	-0.6	+0.3
20	21.3	75.5	28.8	70	22	44	+1.0	-0.9	+0.1
21	19.8	81.5	32.7	62	27	53	+1.0	-0.7	+0.3
22	19.2	79.5	33.6	70	25.5	48	+1.0	-0.8	+0.2
23	22.2	78.0	42.5	95	24	49	+1.0	-0.6	+0.4

Run No.	Particulate								
	Load x 10^3 (g/DNm^3)		d_{pg}		σ_g		n_i x10^{-6}	q' x10	$\frac{\Delta P_t}{q'}$
	In	Out	In	Out	In	Out			
16	147.0	5.8	1.30	0.94	1.9	1.7	2.0	1.8	3.9
17	77.1	4.3	1.32	1.09	2.4	1.5	3.4	2.5	5.6
18	102.6	3.5		Filter run				2.5	3.4
19	75.8	3.5	1.40	1.05	1.9	1.5	0.8	2.8	4.6
20	105.1	24.7		Filter run				2.0	23.5
21	73.6	17.0	1.21	0.98	2.0	1.7	1.6	2.5	23.1
22	79.8	17.2	1.11	0.97	2.2	1.7	3.7	2.9	21.6
23	88.9	6.13	1.45	0.98	2.2	1.6	1.3	3.6	8.9

Table I.2 HORIZONTAL SPRAY SCRUBBER; OPERATING CONDITIONS AND PERFORMANCE

Dust used: Titanium dioxide, -16 mesh
Spray configuration: Cold water sprayed in all of the three sections and drained out through a common outlet. Thus, scrubber operated in the single stage mode.
Inlet water flow rates: First section - 1.05 ℓ/sec @ 2.67 Kg/cm²
Second section - 1.09 ℓ/sec @ 2.67 Kg/cm²
Third section - 1.0 ℓ/sec @ 2.85 Kg/cm²

Run No.	Gas Inlet Conditions				Liquid Temp. (°C)		Scrubber Pressure Differences (cm W.C.)		
	Flow ($\frac{DNm^3}{min}$)	Temp (°C)	Moisture (% vol.)	Relative Humidity (%)	In	Out	ΔP_S	ΔP_E	ΔP_O
24	23.7	10	0.76	71	8	9.5	0.8	1.0	-0.2
25	23.0	12	1.0	68	8	9.5	0.8	1.0	-0.2
26	23.9	11.5	1.1	96	8	9.5	0.8	1.0	-0.2
27	24.2	11	1.4	77	8	9.5	0.8	1.0	-0.2
28	24	11	1.1	77	9	10.5	0.8	1.0	-0.2
29	23	46	10.1	95	16	23.5	0.8	0.9	-0.1
30	22.8	45.5	10.3	97	15.5	21.5	0.8	0.9	-0.1
31	23	45	10	100	14.5	22.5	0.8	1.0	-0.2

Run No.	Particulate								
	Load x 10^3 (g/DNm^3)		d_{pg}		σ_g		n_i x10^{-6}	q' x10	Ef %
	In	Out	In	Out	In	Out			
24	122.4	47.43						--	39.
25	52.3	21.7	1.2	1.02	1.7	1.6	0.6	--	42.
26	97.4	37.8						--	38.
27	98.4	41.6	1.07	1.04	1.8	1.7	1.9	--	42.
28	106	46.6	1.05	0.96	1.8	1.7	2.3	--	44.
29	90.2	9.41	1.2	1.06	1.9	1.6	1.5	0.48	10.
30	104.0	9.47						0.50	92
31	100	11.9	1.06	1.0	1.8	1.7	1.9	0.50	12.

Table I.2 (continued)

Run No.	Gas Inlet Conditions				Liquid Temp. (°C)		Scrubber Pressure Differences (cm W.C.)		
	Flow ($\frac{DNm^3}{min}$)	Temp (°C)	Moisture (% vol.)	Relative Humidity (%)	In	Out	ΔP_S	ΔP_E	ΔP_O
32	22.1	56	17.3	97	16	28	0.8	0.8	0
33	21.9	57	17.4	90	18	31.5	0.8	0.8	0
34	21.7	56	16.4	95	22	34	0.9	0.9	0
35	20.7	66	26.04	95	23	38	0.8	0.8	0
36	20.3	65.5	26.9	100	19	38	0.8	0.8	0
37	19.5	82.5	36.3	66	23	49	0.9	0.8	0.1
38	18.8	73.5	1.2	90	24	48.8	0.8	0.8	0
39	19.6	84.5	35.1	60	22	47.5	0.9	0.7	0.2
40	19.6	84.5	36	57	22	47.5	0.9	0.7	0.2

Run No.	Particulate								
	Load x 10^3 (g/DNm^3)		d_{pg}		σ_g		n_i x10^{-6}	q' x10	Ef %
	In	Out	In	Out	In	Out			
32	133	6.02	1.23	0.9	1.9	1.9	2.0	1.01	045
33	128	5.98	----	Filter	Run	----	-------	0.97	047
34	101	9.29	1.04	0.84	1.5	1.5	1.3	1.01	092
35	121.0	8.59	1.01	0.79	1.6	1.7	1.9	1.9	071
36	158.0	6.37	----	Filter	Run	----	-------	1.75	040
37	131.0	22.4	1.06	0.88	1.8	1.7	3.1	2.20	17
38	128.4	10.0	1.21	0.77	1.9	1.62	2.1	2.45	078
39	146.0	22.1	1.16	0.96	1.8	1.5	2.3	2.65	15.
40	144.0	22.1	----	Filter	Run	----	-------	2.27	15.

Table 3.3. HORIZONTAL SPRAY SCRUBBER; OPERATING CONDITIONS AND PERFORMANCE

Dust used: Titanium dioxide, -16 mesh
Spray configuration: Scrubber operated in single stage mode. The number of nozzles was decreased to obtain the lower water flowrates, maintaining the small spray drop diameter
Inlet water flowrates: 0.76 ℓ/sec in each section

Run No.	Gas Inlet Conditions				Liquid Temp. (°C)		Scrubber Pressure Differences (cm W.C.)		
	Flow ($\frac{Dm^3}{min}$)	Temp (°C)	Moisture (% vol.)	Relative Humidity (%)	In	Out	ΔP_S	ΔP_E	ΔP_O
41	25.37	11	.77	56	10.5	10.1	0.8	-1.0	-0.2
42	22.32	45	10.0	100	18.4	26.4	0.7	-0.9	-0.2
43	22.2	45	9.8	97	14.8	12.5	0.7	-0.9	-0.2
44	22.4	46	10.1	94	13.9	22.7	0.7	-0.8	-0.2
45	21.7	56	16.5	95	18.8	31.3	0.8	-0.8	---
46	22.0	57	16.9	95	18.5	31.3	0.8	-0.8	---
47	22.1	56	16.9	98	18.1	30.8	0.8	-0.8	---
48	20.8	66	25.6	95	20.6	40.0	0.8	-0.8	---
49	20.4	68	26.7	91	22.0	42.5	0.8	-0.8	---
50	20.5	66	26.8	98	21.8	41.5	0.8	-0.8	---

Run No.	Particulate								
	Load x 10^3 (g/Dm^3)		d_{pg}		σ_g		n_i x10^{-4}	q' x10	$\frac{\Delta P_T}{\Phi}$
	In	Out	In	Out	In	Out			
41	72.3	20.2	1.5	.82	2.9	1.5	1.0	---	27.9
42	77.1	9.7	.78	.64	2.0	1.7	7.7	.48	12.6
43	99.8	11.5	.94	.85	1.8	1.6	2.9	.49	11.5
44	121.5	10.1	-----	Filter Run		-------		.52	8.3
45	72.4	4.1	1.05	1.05	1.6	1.6	1.11	.94	5.7
46	84.2	2.6	1.1	.9	1.8	1.7	1.73	.98	5.0
47	97.8	5.2	-----	Filter Run		-------		.99	5.3
48	66.4	2.8	.92	1.1	1.6	2.2	1.5	1.66	4.25
49	161.9	4.8	-----	Filter Run		-------		1.77	2.95
50	77.2	5.3	.96	.96	1.7	1.7	1.7	1.78	4.27

Table 3.4. HORIZONTAL SPRAY SCRUBBER; OPERATING CONDITIONS AND PERFORMANCE

Dust used: Titanium dioxide, -16 mesh
Spray configuration: Scrubber operated in the single stage mode. The lower water flowrates were sprayed through same number of nozzles, thus the spray drops were of larger size.
Inlet water flowrates: 0.76 ℓ/sec in each section

Run No.	Gas Inlet Conditions				Liquid Temp. (°C)		Scrubber Pressure Differences (cm W.C.)		
	Flow ($\frac{Dm^3}{min}$)	Temp (°C)	Moisture (% vol.)	Relative Humidity (%)	In	Out	ΔP_S	ΔP_E	ΔP_O
S1	23.7	17	1.4	64	9.6	11.5	0.4	-0.9	-0.5
S2	23.7	15	1.2	66	10.4	11.5	0.4	-0.9	-0.5
S3	23.8	10	1.1	82	9.6	10.4	0.4	-0.8	-0.4
S4	23.7	12	1.1	73	10.4	11.2	0.4	-0.9	-0.5
S5	24.6	14	1.0	65	10.4	11.5	0.9	-1.0	-0.1
S6	24.3	10	0.9	79	10.4	10.8	0.9	-1.0	-0.1
S7	21.9	46	1.4	94	17.2	26.7	0.4	-0.8	-0.4
S8	22.1	47	1.3	92	16.9	26.7	0.5	-0.8	-0.3

Run No.	Particulate								
	Load x 10^3 (g/Dm^3)		d_{pg}		σ_g		n_i x10^{-4}	q' x10	$\frac{\Delta P_T}{\Phi}$
	In	Out	In	Out	In	Out			
S1	91.3	56.2	1.06	1.04	1.8	1.6	2.0	---	61.6
S2	60.0	45.1	----	Filter Run		-------		---	75.2
S3	81.3	49.4	----	Filter Run		-------		---	60.8
S4	57.2	39.9	.98	1.03	1.7	1.6	1.3	---	69.7
S5	72.8	31.4	1.01	.96	1.8	1.6	1.4	---	43.2
S6	77.3	33.8	1.03	.94	1.7	1.6	1.5	---	43.7
S7	75.8	16.1	----	Filter Run		-------		.47	21.2
S8	102.9	24	----	Filter Run		-------		.47	23.3

Table 7.4 (continued)

Run No.	Gas Inlet Conditions: Flow ($\frac{DNm^3}{min}$)	Temp (°C)	Moisture (% vol.)	Relative Humidity (%)	Liquid Temp. (°C): In	Out	Scrubber Pressure Differences (cm W.C.): ΔP_S	ΔP_E	ΔP_O
59	22	47	1.3	92	17.2	25.5	0.5	-0.8	-0.3
60	21.9	47	1.4	95	16.6	21.9	0.4	-0.7	-0.3
61	21.7	57	.56	90	15.6	28.8	0.5	-0.7	-0.2
62	21.4	58	.59	88	16.7	30	0.5	-0.7	-0.2
63	21.5	57	.61	93	16.9	30	0.5	-0.8	-0.3
64	21.3	58	.57	90	16	28.8	0.5	-0.8	-0.3
65	21.5	57	.60	95	14.1	28.1	0.5	-0.8	-0.3
66	20.8	66	.83	91	19.6	41.9	0.5	-0.8	-0.3

Run No.	Particulate: Load x 10^3 (g/DNm^3): In	Out	d_{pg}: In	Out	σ_g: In	Out	n_i x10^{-6}	q' x10	$\frac{Ft}{k}$
59	83.2	25.7	1.07	.91	1.7	1.5	.98	.49	30.9
60	66.6	14.6	1.1	.95	1.8	1.6	1.6	.49	21.9
61	86.7	21.3	1.14	.92	1.6	1.7	1.0	.92	24.5
62	86.6	14.9	----	Filter	Run	----	------	.97	17.2
63	108.6	21.9	1.15	.94	1.7	1.6	1.4	.99	20.2
64	93.8	10.1	1.11	.92	1.7	1.5	1.5	1.0	10.8
65	64.3	7.9	----	Filter	Run	----	------	1.1	12.3
66	94.4	9.3	1.15	.89	1.7	1.5	1.4	1.5	9.8

Table 7.4 (continued)

Run No.	Gas Inlet Conditions: Flow ($\frac{DNm^3}{min}$)	Temp (°C)	Moisture (% vol.)	Relative Humidity (%)	Liquid Temp. (°C): In	Out	Scrubber Pressure Differences (cm W.C.): ΔP_S	ΔP_E	ΔP_O
67	19.9	68	.68	86	18.9	44.4	0.5	-0.8	-0.3
68	20.9	66	.84	95	18.9	42.5	0.5	-0.8	-0.3
69	20.8	67	.62	92	18	40.6	0.5	-0.7	-0.2
70	20.5	67	.62	96	18.3	39.4	0.5	-0.7	-0.2
71	19.4	73	1.2	94	22	49.4	0.6	-0.7	-0.1
72	19.8	73	.8	96	20.8	49.4	0.5	-0.7	-0.2
73	19.3	74	1.2	92	22.3	50.5	0.6	-0.7	-0.1
74	19.1	73	1.1	96	22.2	49.3	0.6	-0.8	-0.2

Run No.	Particulate: Load x 10^3 (g/DNm^3): In	Out	d_{pg}: In	Out	σ_g: In	Out	n_i x10^{-6}	q' x10	$\frac{Ft}{k}$
67	82.7	10.5	1.25	.91	1.7	1.5	.78	1.5	12.7
68	111.2	21.8	----	Filter	Run	----	------	1.7	19.6
69	109.1	10.7	----	Filter	Run	----	------	1.8	9.8
70	115.5	13.8	1.2	.95	1.8	1.6	1.4	1.9	12
71	99.3	13	1.18	.92	1.8	1.6	1.4	2.4	13.1
72	122.6	10.3	1.13	.95	1.8	1.5	2.0	2.5	8.4
73	129.2	12.7	----	Filter	Run	----	------	2.6	9.8
74	117.9	9.7	----	Filter	Run	----	------	2.7	8.2

Table I.5 HORIZONTAL SPRAY SCRUBBER; OPERATING CONDITIONS AND PERFORMANCE

Dust used: Titanium dioxide, -16 mesh
Spray configuration: Scrubber operated in three stage mode. Cold water sprayed into the first section. The drained water of section 1 resprayed into section 2 and the drain of section 2 sprayed into section 3. Thus, the scrubber is operated in co-current scheme.
Spray water flow rates: First Section: 1.05 liters/sec @ 2.67 Kg/cm²
Second Section: 1.09 liters/sec @ 2.67 Kg/cm²
Third Section: 1.0 liters/sec @ 2.85 Kg/cm²

Run No.	Gas Inlet Condition				Liquid Temperature						Scrubber Pressure Differences (cm W.C.)		
	Flow ($\frac{Dm^3}{min}$)	Temp °C	Moisture % vol.	Rel. %Hum.	1st Section		2nd Section		3rd Section				
					In	Out	In	Out	In	Out	ΔP_S	ΔP_E	ΔP_O
75	24.1	17	0.13	42	12.5	12.5	12.5	11.5	13	11.5	0.8	1.0	-0.2
76	24.4	21	0.88	60	13	13	13	12	13.5	11.8	0.9	1.0	-0.1
77	24.4	23	2.7	92	13.5	13.5	13.5	12	14.5	12	0.8	1.0	-0.2
78	24.4	25	2.7	95	14.5	14.5	12	12.5	15.3	12.5	0.8	1.0	-0.2
79	24.7	19.5	0.5	22	10	10	10.5	9	10.5	8	0.9	1.0	-0.1

Run No.	Particulate								
	Loadx10^3 (g/Dm^3)		d_{pg}, umA		σ_g		$n_i \times 10^{-4}$	$q' \times 10$	$\overline{F_E}$ %
	In	Out	In	Out	In	Out			
75	223.1	84.1	0.95	1.0	2	1.6	5.1	0	38.
76	251.2	100.3	----------	Filter	Run	----------	----------	0	40.
77	245.2	85.6	1.0	2.1	2.1	1.6	5.9	0	35.
78	242.1	82.19	----------	Filter	Run	----------	----------	0	34.
79	189.9	82.1	1.1	1.2	2	1.8	4.7	0	43.

Note: ΔP_S: Pressure difference across the scrubber
ΔP_E: Pressure difference across the entrainment separator
ΔP_O: Overall pressure difference, $\Delta P_S - \Delta P_E$, positive sign denotes pressure gain while pressure loss is denoted by a negative sign.

Table I.5 (continued)

Run No.	Gas Inlet Condition				Liquid Temperature						Scrubber Pressure Differences (cm W.C.)		
	Flow ($\frac{Dm^3}{min}$)	Temp °C	Moisture % vol.	Rel. %Hum.	1st Section		2nd Section		3rd Section				
					In	Out	In	Out	In	Out	ΔP_S	ΔP_E	ΔP_O
80	23.3	46	10	95	15.5	24.5	20.5	25.5	25.5	25.5	0.9	0.9	0
81	23.2	45	9.7	97	12.5	22.5	18.5	23.5	23.5	23.5	0.8	0.9	-0.1
82	23.0	46.5	9.5	97	14	23.5	21.5	25.0	25.0	25.0	0.8	0.9	-0.1
83	22.8	46	9.7	95	18.5	26.5	24	28	28.5	28	0.9	0.9	0
84	22.3	56.5	17.1	92	18	34.2	28.5	35.5	34.5	35.5	0.8	0.8	0
85	22.3	55.5	16.1	96	18	33	22.5	33.5	32	33.5	0.8	0.8	0
86	22.2	55.5	16.1	96	17	35	27	35.5	32.5	35.5	0.8	0.8	0
87	22.2	55.8	16	92	17	32	28.5	33	33	33	0.9	0.9	0
88	22.5	56.5	16.3	92	17	33	19.5	34	31.5	33.5	0.9	0.9	0

Run No.	Particulate								
	Loadx10^3 (g/Dm^3)		d_{pg}, umA		σ_g		$n_i \times 10^{-4}$	$q' \times 10$	$\overline{F_E}$ %
	In	Out	In	Out	In	Out			
80	152.0	22.3	1.3	0.87	2.0	1.5	2.4	0.46	14.7
81	196	19.6	0.87	0.97	2.2	1.6	22.0	0.45	10.
82	199.5	22.8	----------	Filter	Run	----------	----------	0.46	11.4
83	163	20.2	----------	Filter	Run	----------	----------	0.41	12.6
84	162.2	9.7	----------	Filter	Run	----------	----------	0.84	06.1
85	207	16.9	1.3	0.94	1.8	1.5	2.1	0.87	08.2
86	161	13	1.2	0.94	1.8	1.5	2.1	0.87	08.1
87	152	13.8	----------	Filter	Run	----------	----------	0.9	09.1
88	186	15.0	1.2	0.92	1.7	1.6	2.3	0.9	08.1

Table 1.5 (continued)

Run No.	Gas Inlet Condition				Liquid Temperature						Scrubber Pressure Differences (cm W.C.)		
	Flow ($\frac{DNm^3}{min}$)	Temp °C	Moisture % vol.	Rel. Hum.	1st Section		2nd Section		3rd Section				
					In	Out	In	Out	In	Out	ΔP_S	ΔP_B	ΔP_O
89	20.1	66	25.6	94	17.5	42.5	34	45.5	41	45.5	0.8	0.7	0.1
90	20.1	65.5	24.2	94	17.5	42	34.5	43	40.5	42.5	0.8	0.8	0
91	19.6	67	27.2	95	17.5	43.5	33	46	40.5	46	0.8	0.7	0.1
92	20.7	67	26.4	92	16.5	41	34.5	40	40	40	0.8	0.8	0
93	18.2	72.5	35.7	100	16.5	53.5	44.5	51.5	51.5	55	0.8	0.7	0.1
94	19	72.5	35.7	95	17	50.5	40.5	48.5	48.5	53	0.8	0.7	0.1
95	18.8	72.5	36.4	100	17	50.5	41	50	50	54.5	0.9	0.9	0
96	18.7	73	33.8	91	17	54	42.5	51	51	55.5	0.9	0.8	0.1

Run No.	Particulate								
	Loadx10^3 (g/DNm^3)		d_{pg}, umA		σ_g		$n_i \times 10^{-6}$	$q' \times 10$	$\overline{Ft}$ %
	In	Out	In	Out	In	Out			
89	173	14.7	1.2	0.97	1.8	1.5	2.2	1.35	85
90	162	15.1	---------- Filter --- Run ----------					1.35	84
91	158	12.7	1.1	1.05	1.8	1.5	7.6	1.55	8.
92	120	6.48	1.3	0.95	1.7	1.6	4.1	1.53	54
93	154	11.4	---------- Filter --- Run ----------					2.1	74
94	165	9.6	---------- Filter --- Run ----------					2.26	58
95	186	12.4	1.1	0.94	2	1.5	5.4	2.32	67
96	168	15	1.2	0.9	1.8	1.6	2.8	2.07	80

Table 1.6 HORIZONTAL SPRAY SCRUBBER; OPERATING CONDITIONS AND PERFORMANCE

Dust used: Titanium dioxide, -16 mesh
Spray configuration: Scrubber operated in three stage mode. Cold water sprayed into the third section and the scrubber operated in counter-current scheme.
Spray water flow rates: First section: 1.05 ℓ/sec @ 2.67 kg/cm^2
Second section: 1.09 ℓ/sec @ 2.67 kg/cm^2
Third section: 1.0 ℓ/sec @ 2.85 kg/cm^2

Run No.	Gas Inlet Condition				Liquid Temperature						Scrubber Pressure Differences (cm W.C.)		
	Flow ($\frac{DNm^3}{min}$)	Temp °C	Moisture % vol.	Rel. %Hum.	1st Section		2nd Section		3rd Section				
					In	Out	In	Out	In	Out	ΔP_S	ΔP_B	ΔP_O
97	23.4	17.3	10.9	50	7.7	12.0	7.2	11.2	10.1	11.3	0.9	-1.0	-0.2
98	24.0	10.5	10.5	77	10.7	10.4	9.9	10.1	12.5	10.4	0.4	-1.0	-0.6
99	23.4	20	20	41	9.9	11.2	9.9	9.9	11.7	10.9	0.9	-1.0	-0.1
100	23.2	21	21	39	9.2	12.0	9.1	11.7	12.3	12.8	0.8	-1.0	-0.2
101	22.8	23	23	34	9.1	10.7	9.9	9.7	13.2	11.5	0.8	-1.0	-0.2
102	23.2	13	13	54	8.5	9.3	8.9	9.3	12.3	9.6	0.8	-1.0	-0.2

Run No.	Particulate								
	Loadx10^3 (g/DNm^3)		d_{pg}, umA		σ_g		$n_i \times 10^{-6}$	$q' \times 10$	$\overline{Ft}$ %
	In	Out	In	Out	In	Out			
97	64.3	28.7	---------- Filter Run ----------					---	44.6
98	60.3	37.1	---------- Filter Run ----------					---	61.5
99	100.6	44.5	0.98	0.92	1.8	1.5	2.6	---	44.2
100	122.8	51.3	---------- Filter Run ----------					---	41.7
101	95.3	41.4	0.96	0.9	1.7	1.5	2.0	---	43.4
102	79.4	36.0	0.96	0.88	1.7	1.5	1.7	---	45.3

Table 3.6 (continued)

Run No.	Gas Inlet Condition				Liquid Temperature						Scrubber Pressure Differences (cm W.C.)		
	Flow ($\frac{DNm^3}{min}$)	Temp °C	Moisture % vol.	Rel. Hum.	1st Section		2nd Section		3rd Section				
					In	Out	In	Out	In	Out	ΔP_S	ΔP_H	ΔP_O
103	23.8	11	1.1	77	18.1	12.8	17.3	12.8	19.7	12.8	0.4	-0.9	-0.5
104	22.3	46	10.0	94	24.5	31.5	22.9	29.0	18.7	26.7	0.8	-1.0	-0.2
105	22.8	46	10.0	94	25.1	29.8	23.5	26.0	17.1	24.3	0.9	-1.1	-0.2
106	22.9	46.5	10.0	92	23.5	31.5	20.8	26.7	14.4	24.0	0.9	-1.0	-0.1
107	22.7	46.5	10.3	95	24.5	30.0	21.9	26.5	18.1	24.3	0.9	-1.0	-0.1
108	22.5	47.5	10.2	89	25.9	30.5	20.8	26.5	13.3	22.9	0.9	-1.0	-0.1
109	21.7	56.5	16.0	90	30.5	43.8	26.3	37.5	14.4	30	0.8	-0.9	-0.1
110	21.5	56	16.4	95	31.3	44.4	27.5	38.8	16.7	31.3	0.9	-0.9	0.0
111	21.4	56.5	16.8	95	30.6	43.8	27.5	40.0	17.3	32.5	0.9	-1.0	-0.1

Run No.	Particulate								
	Loadx10^3 (g/DNm^3)		d_{pg}, µmA		σ_g		$n_i \times 10^{-6}$	$q' \times 10$	$\overline{Ft}$ %
	In	Out	In	Out	In	Out			
103	76.4	49.8	0.96	1.0	1.8	1.6	2.1	---	65.2
104	106.3	29.8	0.94	0.84	1.6	1.5	2.4	0.47	28.0
105	68.4	16.0	1.0	0.82	1.6	1.5	1.2	0.47	23.4
106	107.8	17.9	----------	--- Filter Run	-----	----------	----------	0.48	16.6
107	110.6	31.0	----------	--- Filter Run	-----	----------	----------	0.50	28.0
108	68.3	11.5	0.94	0.92	1.7	1.6	1.7	0.52	16.8
109	96.6	13.6	1.1	0.82	1.6	1.6	1.2	0.87	14.1
110	127.5	22.4	----------	--- Filter Run	-----	----------	----------	0.9	17.5
111	133.4	19.1	----------	--- Filter Run	-----	----------	----------	0.9	14.3

Table 3.6 (continued)

Run No.	Gas Inlet Condition				Liquid Temperature						Scrubber Pressure Differences (cm W.C.)		
	Flow ($\frac{DNm^3}{min}$)	Temp °C	Moisture % vol.	Rel. Hum.	1st Section		2nd Section		3rd Section				
					In	Out	In	Out	In	Out	ΔP_S	ΔP_H	ΔP_O
112	21.1	56.5	16.9	95	31.9	41.3	30.0	38.3	20.0	35.6	0.9	-0.9	-0.1
113	21.5	57.5	17.2	93	33.1	42.5	30.0	38.8	18.7	30.6	0.9	-1.0	0.0
114	20.4	66	26.2	96	43.8*	57.2	38.8	53.6	18.7	42.5	0.9	-0.9	-0.1
115	20.8	66	25.5	93	43.8	56.0	38.8	51.1	19.3	41.3	0.9	-0.9	0.0
116	20.1	66	25.6	93	47.0	54.8	40.0	51.1	19.7	40.0	0.9	-0.9	0.0
117	19.9	68	27.3	91	45.6	58.4	42.5	54.8	20.0	43.8	0.9	-0.9	0.0
118	20.2	67.5	26.7	91	45.0	55.4	40.0	51.1	18.7	41.3	0.9	-0.9	0.0
119	19.3	74	34.7	90	52.3	67.0	48.8	62.1	20.7	52.3	0.9	-0.9	0.0
120	19.6	73	36.3	100	50.5	65.7	48.8	63.3	24.0	52.3	0.9	-0.9	0.0

Run No.	Particulate								
	Loadx10^3 (g/DNm^3)		d_{pg}, µmA		σ_g		$n_i \times 10^{-6}$	$q' \times 10$	$\overline{Ft}$ %
	In	Out	In	Out	In	Out			
112	109.6	19.9	1.03	0.85	1.5	1.5	1.3	0.9	18.2
113	86.8	13.2	1.2	0.82	1.6	1.5	0.7	0.95	15.2
114	134.1	32.6	1.03	0.82	1.7	1.6	2.5	1.5	21.2
115	150.5	23.5	1.1	0.88	1.6	1.5	2.1	1.5	15.6
116	167.6	42.0	----------	--- Filter Run	-----	----------	----------	1.5	25.1
117	131.0	24.1	1.0	0.86	1.6	1.5	2.6	1.5	18.4
118	140.5	29.8	----------	--- Filter Run	-----	----------	----------	1.6	21.2
119	129.4	24.3	----------	--- Filter Run	-----	----------	----------	2.1	16.8
120	169.6	20.0	----------	--- Filter Run	-----	----------	----------	2.3	11.8

Table 1.6 (continued)

Run No.	Gas Inlet Condition				Liquid Temperature						Scrubber Pressure Differences (cm W.C.)		
	Flow ($\frac{DNm^3}{min}$)	Temp °C	Moisture % vol.	Rel. Hum.	1st Section		2nd Section		3rd Section				
					In	Out	In	Out	In	Out	ΔP_S	ΔP_E	ΔP_O
121	18.1	74	36.3	94	47.5	64.5	43.8	60.9	21.3	50.0	0.9	-0.8	0.1
122	19.4	73.5	36.3	96	48.1	64.5	43.8	60.9	21.3	49.9	0.9	-0.9	0.0
123	19.1	71	33.2	98	49.9	63.3	45.6	59.7	16.0	48.8	0.8	-0.8	0.0

Run No.	Particulate								
	Loadx10^3 (g/DNm^3)		d_{pg}, µmA		σ_g		$n_i \times 10^{-6}$	$q' \times 10$	$\overline{Pt}$ %
	In	Out	In	Out	In	Out			
121	135.4	9.0	1.23	0.88	1.8	1.6	1.7	2.5	6.7
122	98.3	12.4	1.12	0.82	1.7	1.5	1.4	2.5	12.6
123	76.8	10.0	1.05	0.8	1.7	1.4	1.2	3.0	13.0

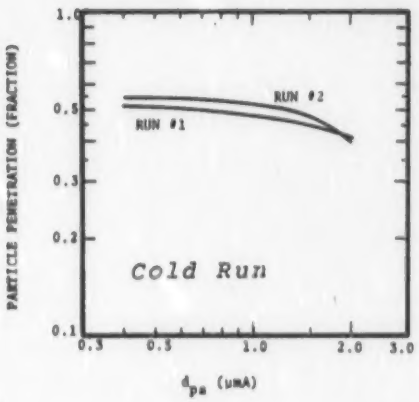

Figure 1.1 - Particle penetration versus aerodynamic diameter, single stage spray scrubber.

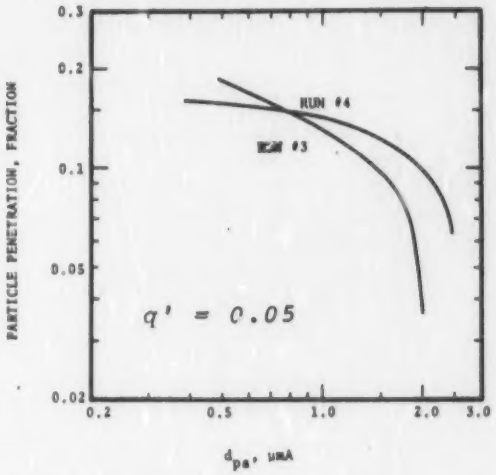

Figure 1.2 - Particle penetration versus aerodynamic diameter, single stage spray scrubber.

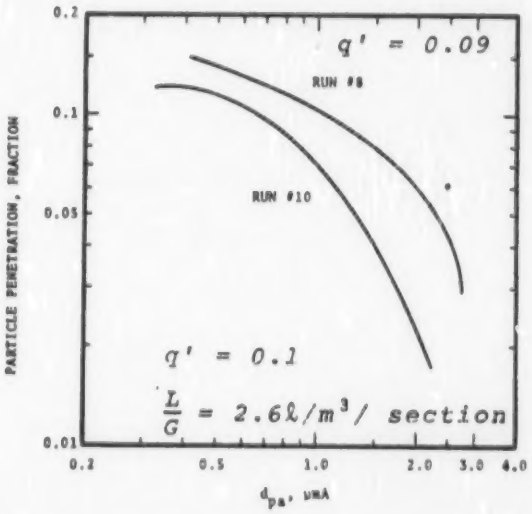

Figure 1.3 - Particle penetration versus aerodynamic diameter, single stage spray scrubber.

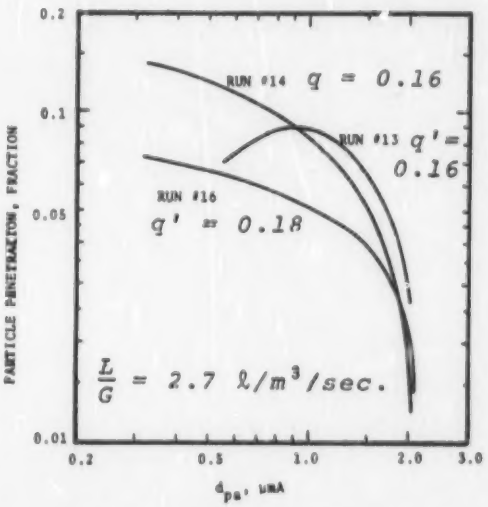

Figure 1.4. - Particle penetration versus aerodynamic diameter, single stage spray scrubber.

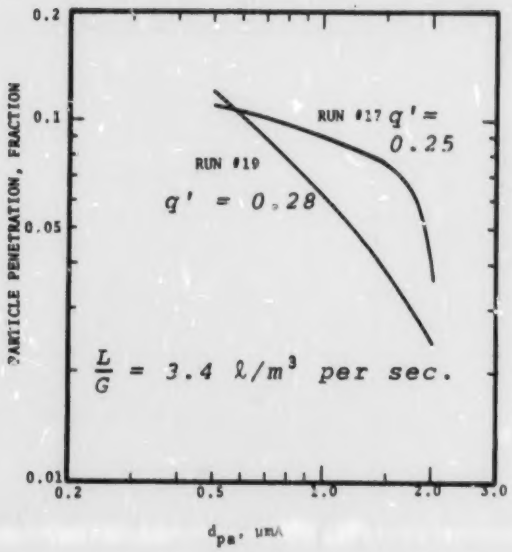

Figure 1.5. - Particle penetration versus aerodynamic diameter, single stage spray scrubber.

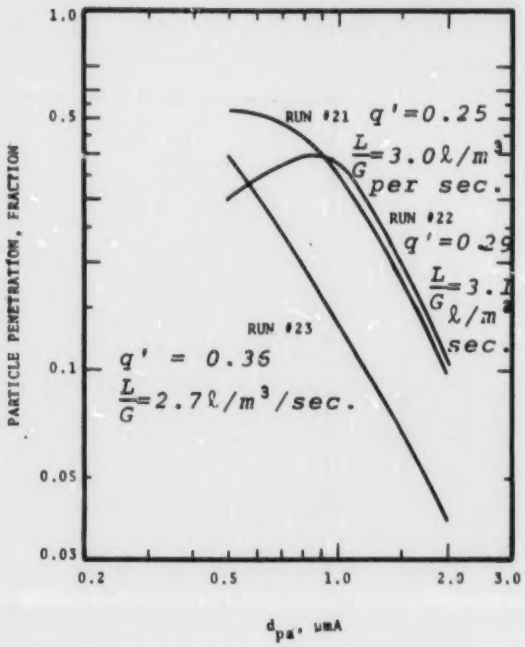

Figure 1.6. - Particle penetration versus aerodynamic diameter, single stage spray scrubber

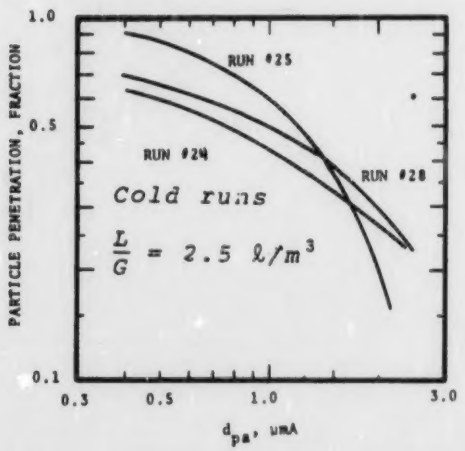

Figure 1.7. - Particle penetration versus aerodynamic diameter, single stage spray scrubber.

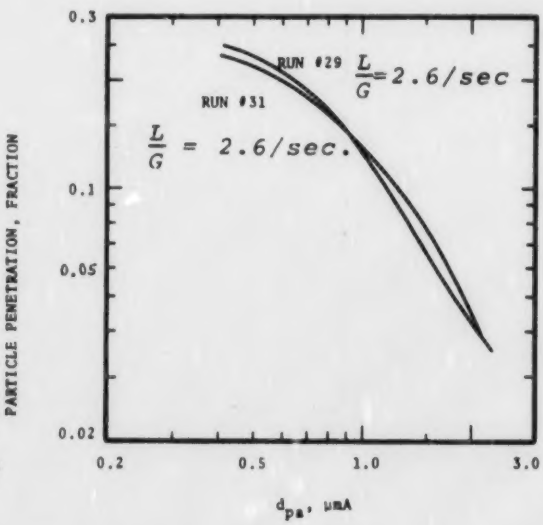

Figure 1.8. - Particle penetration versus aerodynamic diameter, single stage spray scrubber.

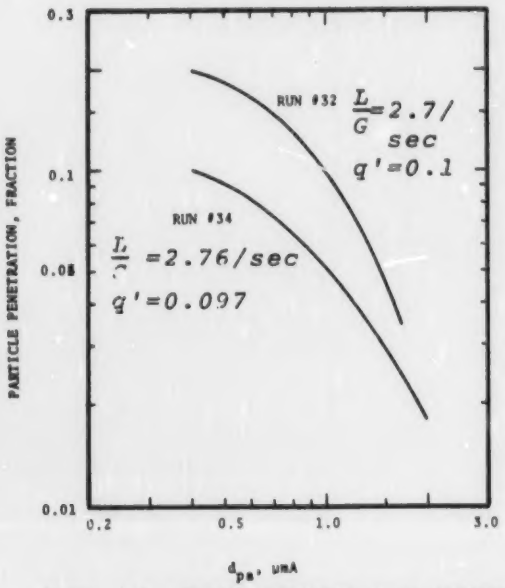

Figure 1.9. - Particle penetration versus aerodynamic diameter, single stage spray scrubber.

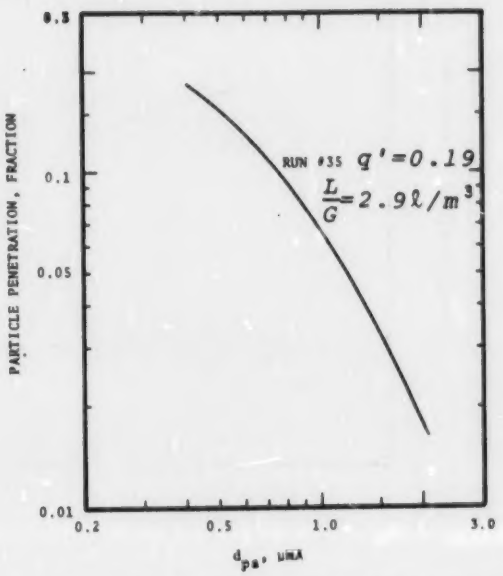

Figure 1.10. - Particle penetration versus aerodynamic diameter, single stage spray scrubber.

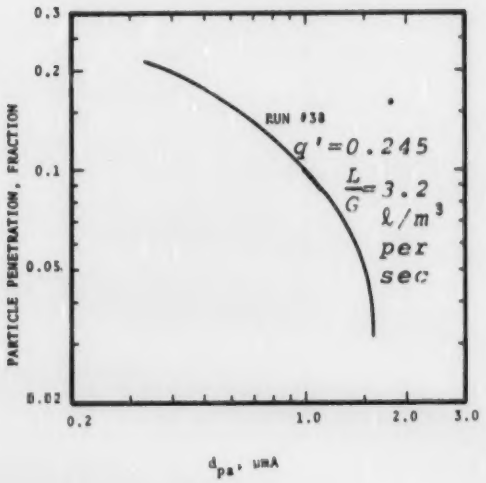

Figure 1.11. - Particle penetration versus aerodynamic diameter, single stage spray scrubber.

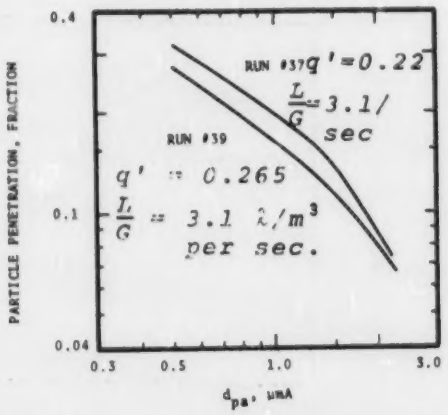

Figure 1.12. - Particle penetration versus aerodynamic diameter, single stage spray scrubber.

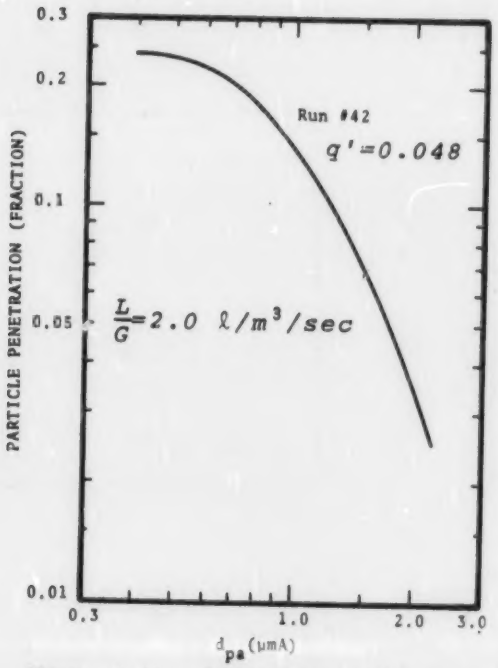

Figure | .13 - Particle penetration versus aerodynamic diameter, one stage.

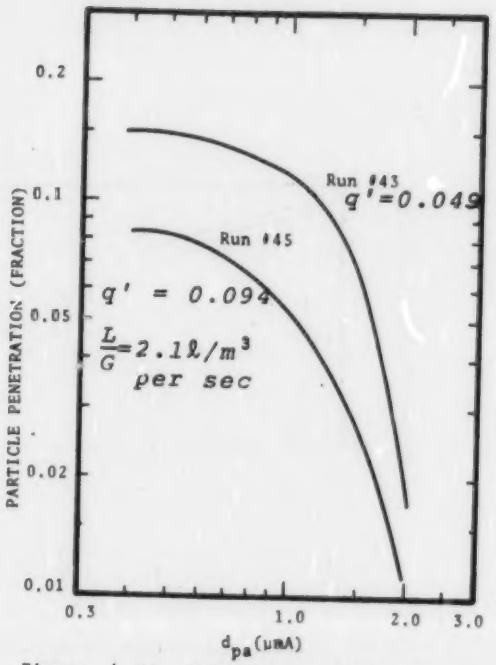

Figure | .14 - Particle penetration versus aerodynamic diameter, one stage.

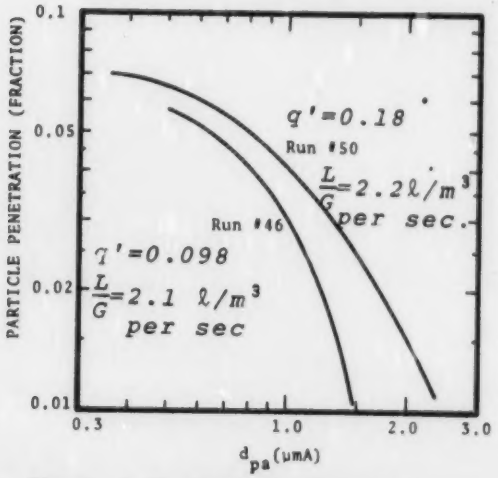

Figure | .15 - Particle penetration versus aerodynamic diameter, one stage.

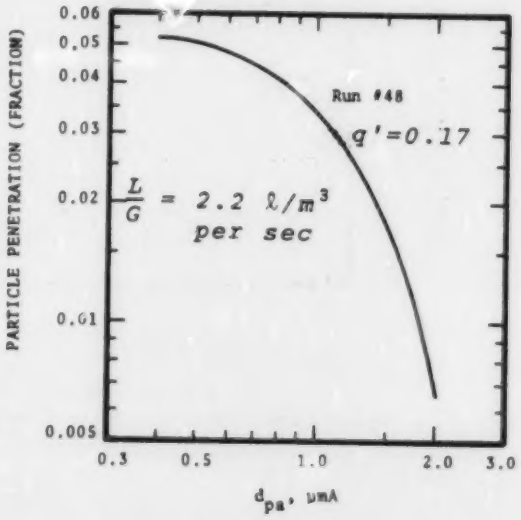

Figure | .16 - Particle penetration versus aerodynamic diameter, single stage.

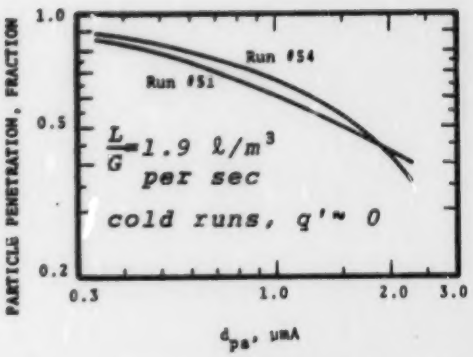

Figure 1.17 - Particle penetration versus aerodynamic diameter, one stage.

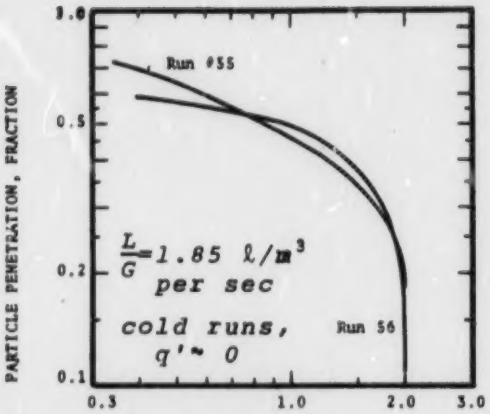

Figure 1.18 - Particle penetration versus aerodynamic diameter, one stage.

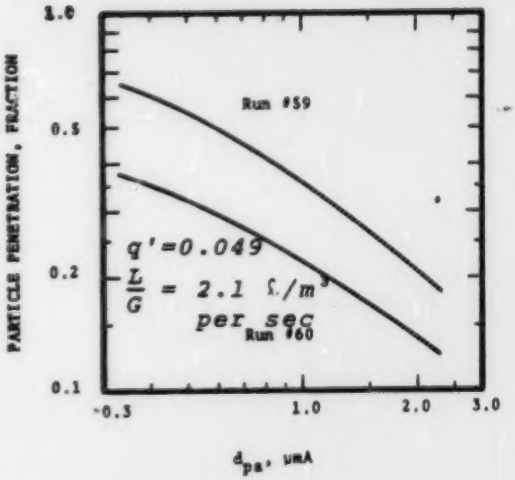

Figure 1.19 - Particle penetration versus aerodynamic diameter, one stage.

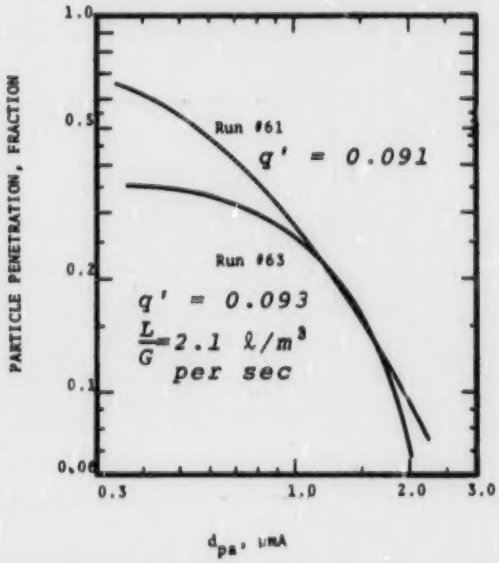

Figure 1.20 - Particle penetration versus aerodynamic diameter, one stage.

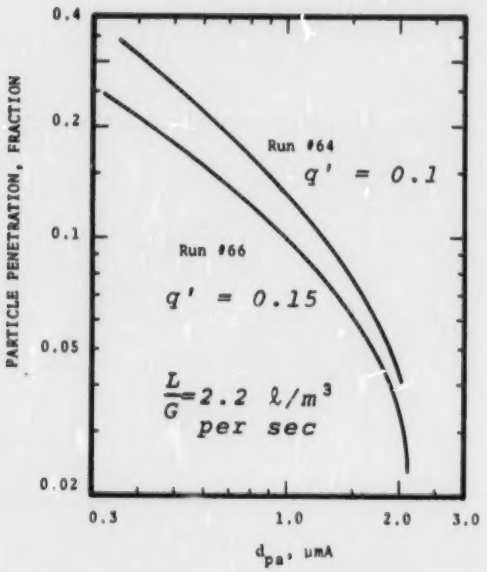

Figure 1.21 - Particle penetration versus aerodynamic diameter, one stage.

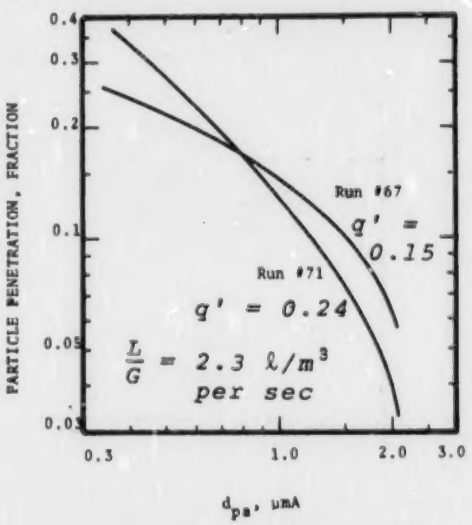

Figure 1.22- Particle penetration versus aerodynamic diameter, one stage.

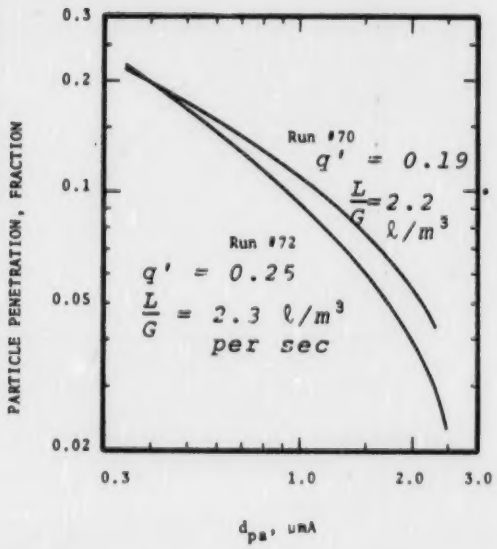

Figure 1.23 - Particle penetration versus aerodynamic diameter, one stage.

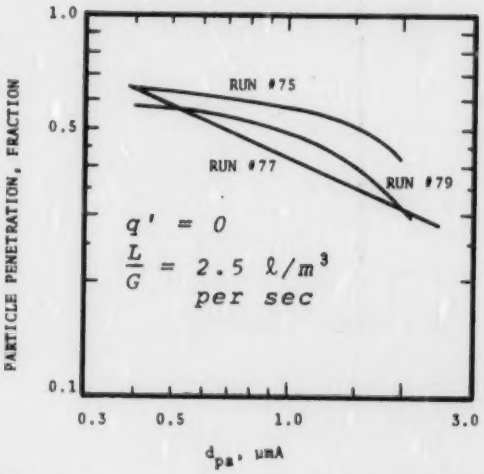

Figure 1.24 - Particle penetration versus aerodynamic diameter, 3 stage co-current spray scrubber.

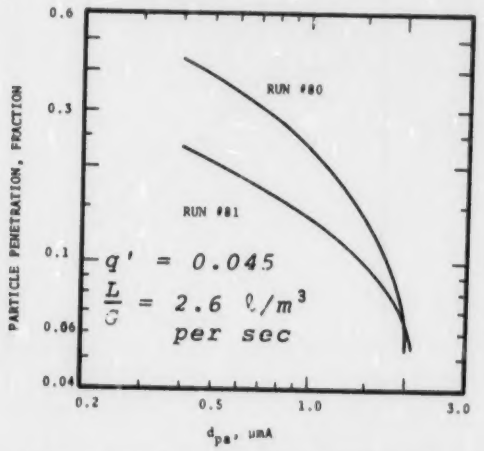

Figure 1.25 - Particle penetration versus aerodynamic diameter, 3 stage co-current spray scrubber.

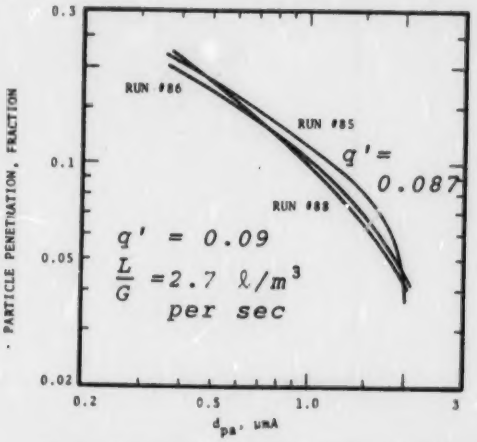

Figure 1.26 - Particle penetration versus aerodynamic diameter, three stage co-current spray scrubber.

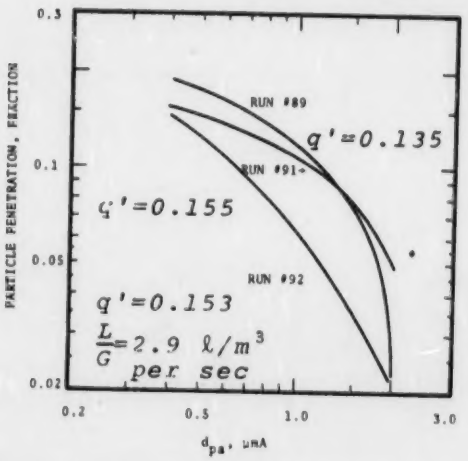

Figure 1.27 - Particle penetration versus aerodynamic diameter, three stage co-current spray scrubber.

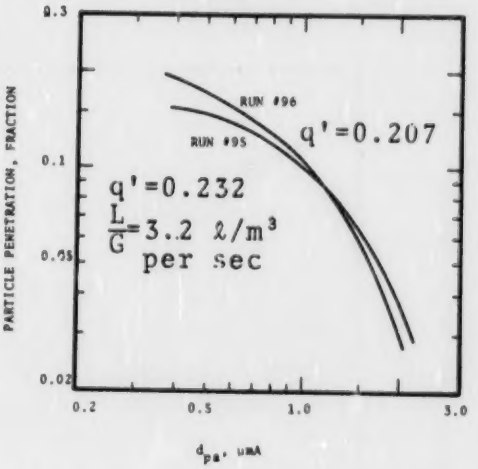

Figure 1.28 - Particle penetration versus aerodynamic diameter, three stage co-current spray scrubber.

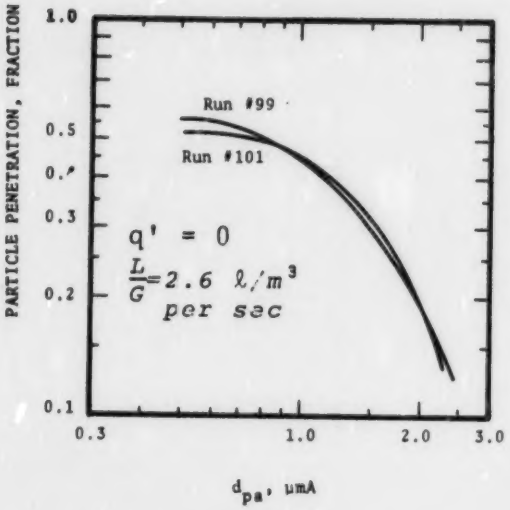

Figure 1.29 - Particle penetration versus aerodynamic diameter, three stage counter-current.

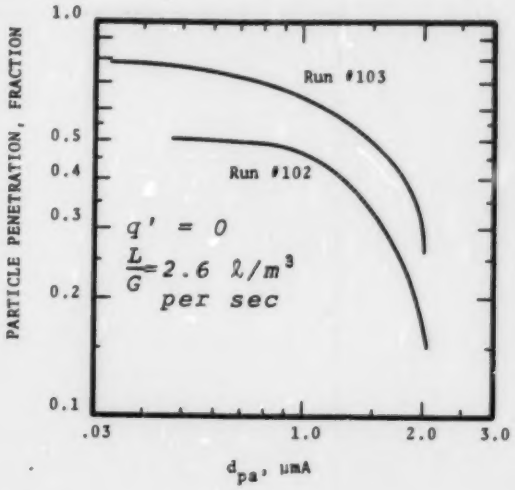

Figure 1.30 - Particle penetration versus aerodynamic diameter, three stage counter-current.

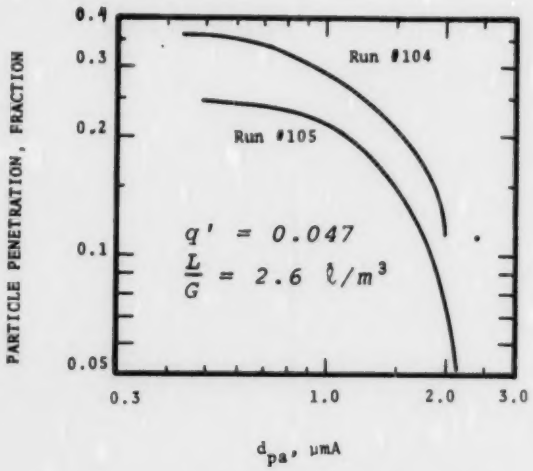

Figure 1.31 - Particle penetration versus aerodynamic diameter, three stage counter-current.

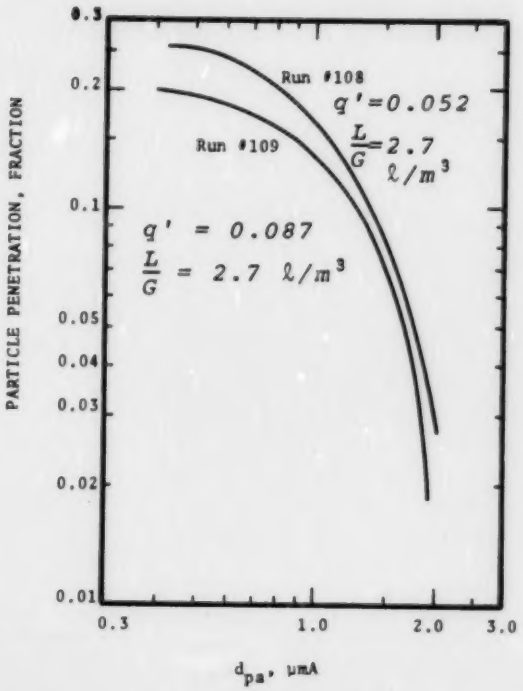

Figure 1.32 - Particle penetration versus aerodynamic diameter, three stage counter current.

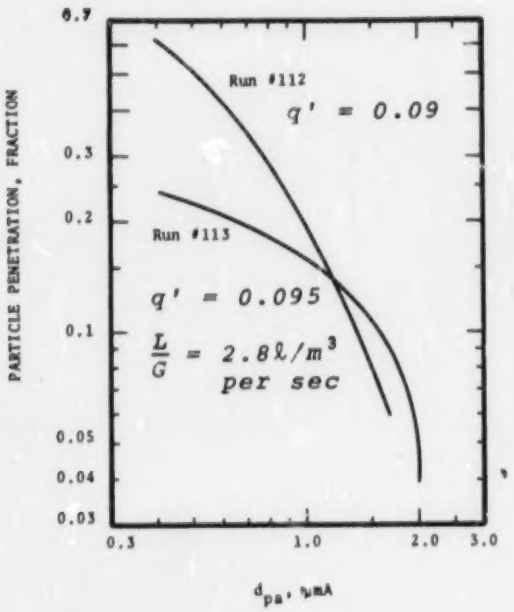

Figure 1.33 - Particle penetration versus aerodynamic diameter, three stage counter-current.

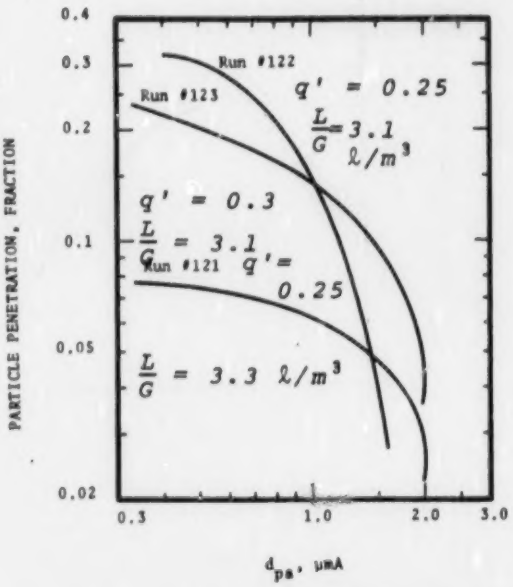

Figure 1.34 - Particle penetration versus aerodynamic diameter, three stage counter-current.

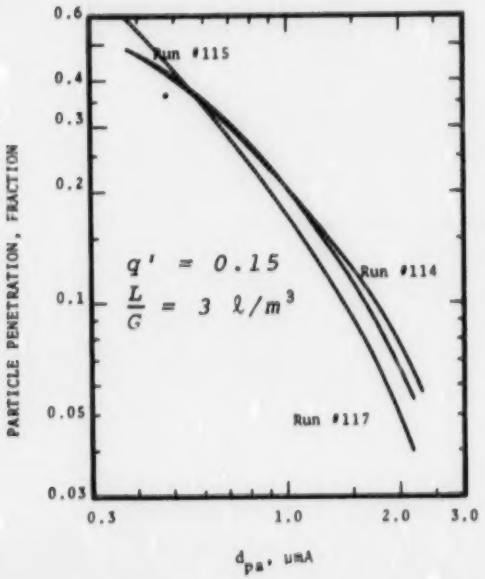

Figure 1.35- Particle penetration versus aerodynamic diameter, three stage counter-current